

RESEARCH MEMORANDUM

INVESTIGATION OF AXIALLY SYMMETRIC AND TWO-DIMENSIONAL
MULTINOZZLES FOR PRODUCING SUPERSONIC STREAMS

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NATIONAL ADVISORY COMMITTEE
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SUMMARY

The flow characteristics of three axially symmetric multinozzles of nominal design Mach numbers 3.46, 3.07, and 7.01 and a two-dimensional multinozzle of nominal design Mach number 3.07 were investigated. Three types of disturbance, classified as oblique shock waves, corner shock waves, and wakes, were observed in the flow fields. The effect of the geometry of the multinozzles on these disturbances and on the actual Mach number and pressure recovery obtained with the multinozzle is discussed herein.

The magnitude of the disturbances was found to depend on the exit turning angle of the individual nozzles. Generally, Mach number variations of $4\frac{1}{2}$ percent or less existed in a region which could be used as a test section. The use of multinozzles, however, appears to be restricted to experiments in which nonuniformity of flow and large pressure losses can be tolerated and for which simple fabrication and quick interchange of nozzles are desired.

INTRODUCTION

A multinozzle for producing supersonic streams is a planar set of nozzles (such as a plate perforated with holes) mounted across a channel or duct. If the axial pressure differential across the nozzles exceeds a critical value, the air flowing through the nozzles is expanded to supersonic velocities. The uniformity and velocity of the supersonic flow downstream of the multinozzle depend on the impingement and mixing of the flow from adjacent nozzles and on the flow reflections from the walls of the duct.

An advantage of multinozzles is their short length as compared with the lengths of conventional supersonic nozzles. Because of this short length, multinozzles can be made readily interchangeable to provide

various test Mach numbers in a single facility. In addition, secondary flows which cause nonuniform boundary-layer growth along the side-wall center lines of conventional two-dimensional nozzles (reference 1) are eliminated so that the boundary-layer thickness is uniform on all walls of the duct.

The original investigations in multinozzles are attributed to Ludwig. Additional work on the flow characteristics downstream of axially symmetric and two-dimensional multinozzles is reported in references 2 and 3. (In referring to the two types of multinozzle, the terms "axially symmetric" and "two-dimensional" refer to the shape of the individual nozzle.) Similar investigations with multinozzles fabricated from wire-mesh screening are reported in reference 4.

In the investigation of reference 2, the stream static pressure in the plane transverse to the duct axis was assumed equal to the static pressure at the duct axis. Measurements of static pressure downstream of multinozzles indicate, however, that this may not be a valid assumption.

Reference 3 used a method for evaluating the flow characteristics which depends on accurate measurements from schlieren photographs. The data obtained from the schlieren measurements indicated good flow uniformity; yet pressures measured with a pitot-pressure probe were discounted because their fluctuations were as great as ± 10 percent.

The results of these investigations nevertheless indicated that the uniformity of the supersonic flow was generally poorer than could be obtained with a single nozzle because of the many shock waves and wakes which propagated downstream. Also, differences in the flow obtained with axially symmetric and with two-dimensional multinozzles were noted. The axially symmetric multinozzle yielded greatly increased total-pressure losses as the design Mach number was increased; whereas the two-dimensional multinozzles, while giving good pressure recoveries, had noticeable wakes downstream of each strip of the multinozzle. These wakes, in which decrements of velocity and total pressure exist, caused distortion of shock patterns in the schlieren photographs making them difficult to read and evaluate.

In the present investigation, which was conducted at the NACA Lewis laboratory, more detailed examination of the effects of multinozzle geometry was made for the purpose of designing multinozzles with satisfactory flow characteristics for wind-tunnel studies at supersonic Mach numbers. Schlieren photographs and transverse and axial variations of Mach number and static pressure are presented for multinozzles with various internal contours, nozzle lengths (plate thicknesses), and array geometries. Results are compared for three axially symmetric multinozzles designed for Mach numbers of 3.46, 3.07, and 7.01 and for one two-dimensional multinozzle designed for a Mach number of 3.07.

SYMBOLS

The following symbols are used in this report:

- A_m minimum flow area in multinozzle
 A_s total stream cross-sectional area
 M Mach number
 M_a average stream Mach number at station of most uniform flow in second test section
 M_d nominal design Mach number
 P total pressure
 p static pressure
 x axial distance from multinozzle
 y transverse distance from duct center line

Subscripts:

- 0 conditions upstream of multinozzle
 1 stream conditions in plane of probe traverse

DESCRIPTION OF APPARATUS

General features of the four multinozzles considered in this investigation are as follows:

Multinozzle	Nozzle type	Plate thickness (in.)	A_s/A_m	M_d	Array geometry
a	axially symmetric	1/4	6.54	3.46	square
b	axially symmetric	3/4	4.51	3.07	triangular
c	axially symmetric	1/2	105.1	7.01	triangular
d	two-dimensional	1/4	4.50	3.07	-----

The relation between A_s/A_m and the nominal design Mach number is for one-dimensional flow. These multinozzles are illustrated in figure 1.

Multinozzles a, b, and d were investigated in a 3.4- by 3.4-inch duct (fig. 2(a)), and multinozzle c was investigated in a 6- by 6-inch

duct (fig. 3(a)). The static- and pitot-pressure probes used in each of the ducts are illustrated in figures 2(b) and 3(b). The instruments and manometer fluid used for the pressure measurements were as follows:

Pressure measured	Duct			
	3.4- by 3.4-inch		6- by 6-inch	
	Instrument	Manometer fluid	Instrument	Manometer fluid
Inlet total	Pitot probe	Tetrabromoethane	Diaphragm gage	-----
Stream pitot	Pitot probe	Tetrabromoethane	Pitot probe	Mercury
Stream static	Static probe	Mercury	Static probe	Butyl phthalate
Wall static	Wall taps	Mercury	Wall taps	Butyl phthalate

In each duct the wall static-pressure taps were spaced along the center line of one of the walls. Also, movable schlieren apparatus which permitted observation of the flow over most of the lengths of the ducts were employed.

The operating conditions of each of the ducts were as follows:

Duct	Dew-point temperature (°F)	Inlet temperature (°F)	Inlet pressure (lb/sq in. abs)	Reynolds number per foot $\times 10^{-6}$
3.4- by 3.4-inch	0 $\pm$ 10	110 $\pm$ 20	atmospheric	0.7-1.7
6- by 6-inch	<-20	80 to 220	214 $\pm$ 2	1.1-2.1

There was no noticeable change in flow conditions because of the inlet temperature variation in the 6- by 6-inch duct. Also, for one test in the 6- by 6-inch duct the inlet pressure was increased to 415 pounds per square inch absolute with no significant change in the measured Mach number profiles.

DISCUSSION AND RESULTS

The two main criteria used in evaluating multinozzle performance are (1) uniformity of the flow in the test section and (2) the ratio of the average stream total pressure to the total pressure upstream of the multinozzle. This total-pressure ratio and the diffuser efficiency indicate the power requirements of the tunnel.

There are three major types of flow disturbance peculiar to multinozzles - corner shock waves, oblique shock waves, and wakes - all of

which are shown diagrammatically in figure 4. The oblique shock waves and wakes originate at the exit of each of the nozzles, whereas the corner shock waves originate near the four intersections of the multinozzle with the duct walls. Schlieren photographs indicated that both oblique shock waves and wakes were present for small and large exit turning angles. For the larger exit angles, however, the shock waves were stronger and dissipated slowly as the flow proceeded downstream, while the wakes were weaker and dissipated rapidly. For the smaller exit angles, the wakes were stronger and dissipated slowly, while the shock waves were weaker and dissipated quickly. The largest disturbances were generally the corner shocks which bound test sections in which the flow might be expected to be uniform. For a given stream Mach number the strength of the corner shocks depended on the exit angle of the nozzles and on the geometric relation of the edge (outer row) nozzles to the walls of the duct.

Mach number and static-pressure profiles for the four multinozzles tested in this investigation are presented for various axial stations in figures 5 and 6, respectively. The broken lines in each profile indicate the intersection of prominent shock disturbances with the transverse plane as observed from the schlieren photographs of figure 7. (In fig. 7(c), because schlieren photographs are not available in the region of the stations at which probe measurements were made, the approximate location of these intersections was obtained by extending the corner shock lines from their upstream locations.) Generally, the Mach number and static-pressure profiles (figs. 5 and 6) become more uniform with increased distance downstream of the multinozzle. The profiles with the smallest percentage variation of Mach number were obtained in the second test section (fig. 4) downstream of the multinozzle. (Inasmuch as the test sections are bounded by the four corner shocks (fig. 4), the axial location of the second test section varies with Mach number.) For multinozzle (a), comparatively uniform profiles were obtained in the first test section downstream of the multinozzle (figs. 5(a) and 6(a)). The variation in Mach number about the average value for the best profiles within the test sections is about $4\frac{1}{2}$ percent or less and is 6 percent or less for most other profiles. For each multinozzle the static-pressure profiles which correspond to the best Mach number profiles are among the more uniform profiles obtained. For multinozzles (a), (b), and (d) the transverse static-pressure gradient near the wall is not zero because of disturbances generated by the probe or shock in the boundary layer.

Quantitative information on the performance of each multinozzle is summarized in table I. Data are presented for survey stations in the second test section wherein the flow is generally more uniform.

The axial variations of Mach number and static pressure are presented in figure 7 with schlieren photographs of the flow. Generally, the data indicate a decrease in Mach number and an increase in static pressure with distance downstream because of total-pressure losses from wall friction and shocks.

For the Mach number and pressure profiles obtained at $x = 24$ inches with multinozzle (c), seven additional nozzles were added along two edges of the multinozzle to increase the length of the short rows (fig. 1(c)). This modification resulted in smaller stream Mach numbers and larger static pressures throughout the flow field. The variation and the average value of Mach number and the static-pressure variation for this modification are also shown at $x = 44$ in figure 7(c). (This modification is indicated by tailed symbols.)

Except for multinozzle (b), the corner shocks, which were the most prominent disturbances in the stream, propagated downstream through the whole visible portion of the duct. For plate (b), the corner shocks were not well defined in the schlieren photographs (fig. 7(b)). At many axial stations, some of the oblique shocks even appeared to be stronger than the corner shocks. The weaker corner shocks resulted chiefly because plate (b) had the smallest exit turning angle of any of the multinozzles so that the flow deflection at the duct wall was reduced and the strength of the corner shock was decreased. They also may have resulted partly because of the triangular-array geometry in which only alternate nozzles are immediately adjacent to the duct wall on two edges of the array. No effect except this possible decrease in the strengths of the corner shocks was found to result from changing the array of the axially symmetric multinozzles from square to triangular geometry.

The effect of nozzle-exit turning angle on the performance of multinozzle (c) is indicated in figure 8. The exit turning angle was varied as shown by the dashed lines in the nozzle detail of figure 1(c). The largest stream Mach number was obtained for an exit turning angle of 30° . This, then, is the angle at which a good compromise is obtained between the oblique shock and the wake losses for plate (c).

The pressure recoveries P_1/P_0 at the station of most uniform flow in the second test section are shown in figure 9 for each of the multinozzles. For comparison, results from references 2, 3, and 4 are included. Multinozzle (a) yields the poorest recovery of the multinozzles which operate near M_a of 2.25. This is primarily because of its small thickness which necessitates large exit turning angles and consequently stronger shocks. For multinozzle (b), although its greater thickness results in larger friction losses, the small exit turning angles result in a decrease in oblique shock losses. The net pressure recovery is about 24 percentage points greater than that of multinozzle (a).

The pressure recovery of multinozzle (d) is poor compared with the recoveries of the two-dimensional multinozzles reported in references 2 and 3. This is because the elements of multinozzle (d) are relatively thin and were made in a simple shape, with large exit turning angles. Shocks therefore were generated which contributed significantly to the total-pressure losses.

The wakes which are characteristic of the two-dimensional multinozzles reported in references 2 and 3 did not appear in the schlieren photographs of the flow downstream of multinozzle (d), probably because of the rapid dissipation of the wakes in the region of the oblique shocks.

On the basis of the investigations so far conducted, it is felt that the detailed geometry of individual nozzles, whether designed for isentropic expansion or as simple wedges or cones, does not affect the flow characteristics downstream of the multinozzle except as the geometry determines the exit turning angle.

For all the multinozzles the uniformity of the flow is not sufficiently good for most research investigations. Furthermore, pressure recoveries obtained with multinozzles may be as much as 60 percent smaller than those obtained with conventional nozzles. Multinozzles may nevertheless be useful for supersonic studies for which nonuniformity of flow and large pressure losses can be tolerated, and for which simple fabrication and quick interchange of nozzles are desired.

SUMMARY OF RESULTS

Investigations of the supersonic flow field downstream of axially symmetric and two-dimensional multinozzles have established that there are three major disturbances in the stream. These are (a) oblique shocks due to the impingement of jets from adjacent nozzles, (b) wakes propagated directly downstream of the nozzle edges, and (c) corner shocks whose existence, origin, and strength depend on the particular relation of edge nozzles to the walls of the duct. From the tests herein described, the following additional results were obtained:

1. Oblique shock-wave losses predominated at large exit turning angles, whereas wake losses predominated at small exit turning angles.
2. The most uniform Mach number profiles were generally obtained in the second test section downstream of the multinozzle at which the variation in Mach number was about $4\frac{1}{2}$ percent or less.

3. Although an increase in the streamwise thickness of the multi-nozzle resulted in an increase in friction losses, there was a sufficient decrease in shock losses because of reduced exit turning angles to yield a significant net gain in total-pressure recovery. The detailed geometry of the individual nozzles apparently was important only insofar as it defined the exit turning angle.

4. Disadvantages of multinozzles were found to be the nonuniformity of the flow in the test section and the large losses in total pressure.

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REFERENCES

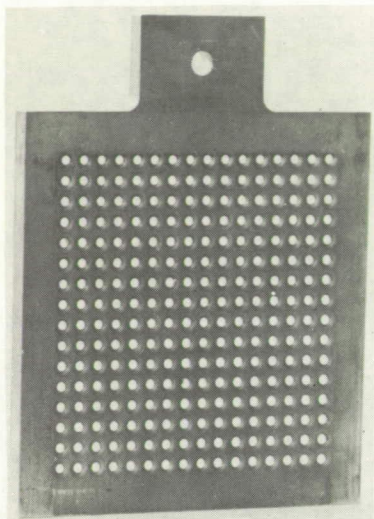
1. Haefeli, Rudolph C.: Use of Fences to Increase Uniformity of Boundary Layer on Side Walls of Supersonic Wind Tunnels. NACA RM E52E19, 1952.
2. Royle, J. K., Bowling, A. G., and Lukasiewicz, J.: Calibration of Two Dimensional and Conical Supersonic Multi-Nozzles. Rep. Aero. 2221, S.D. 23, British R.A.E., Sept. 1947.
3. Kurzweg, H. H.: The Use of Grating Nozzles and Diffusers. Memo. 9848, Naval Ord. Lab. (Maryland), July 29, 1948. (Proj. NOL-4-Re9d-21-2.)
4. Gould, Lawrence I.: Preliminary Investigation of the Supersonic Flow Field Downstream of Wire-Mesh Nozzles in a Constant-Area Duct. NACA RM E51F25, 1951.

TABLE I - MULTINOZZLE PERFORMANCE

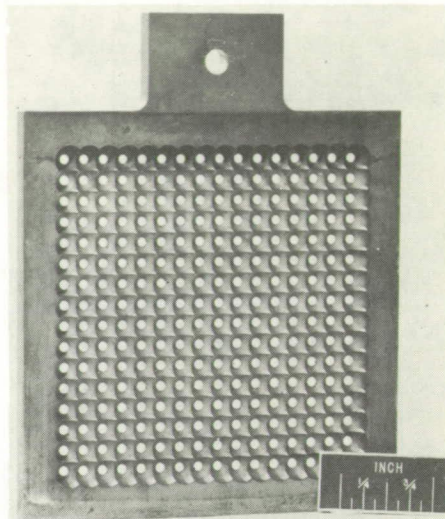
[Values given are for most uniform Mach number profile in second test section]

Multinozzle	M_d	Distance downstream of multinozzle (in.)	M_a	Variation of Mach number about average value (percent)	Variation of static pressure about average value (percent)	One- dimensional pressure recovery	Major disturbances
a	3.46	9.97	2.00	6.2	4.4	0.26	Corner shocks Oblique shocks
b	3.07	16.76	2.34	3.4	6.8	0.50	Oblique shocks
c	7.01	35	3.57	3.5	10.1	0.07	Corner shocks Oblique shocks Wakes
d	3.07	13.38	2.22	4.5	5.5	0.45	Corner shocks Oblique shocks

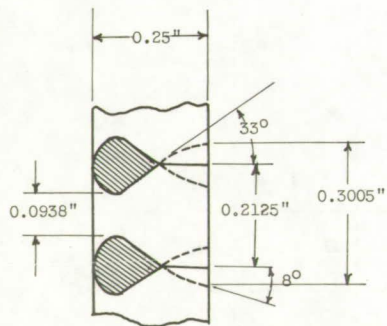




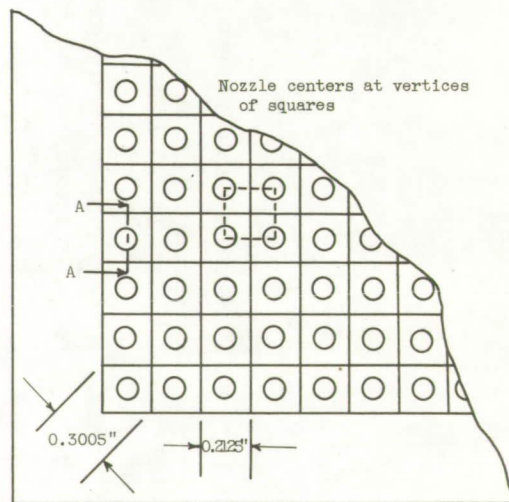
Subsonic side



Supersonic side



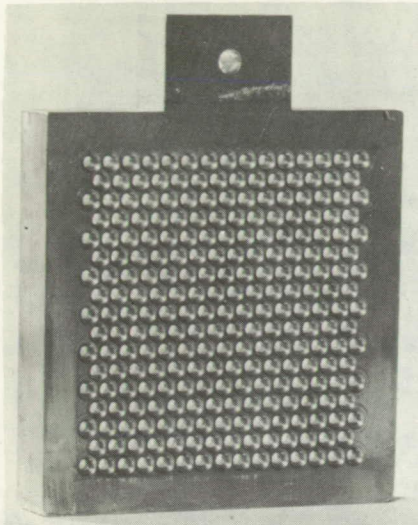
Section A-A
Single nozzle detail



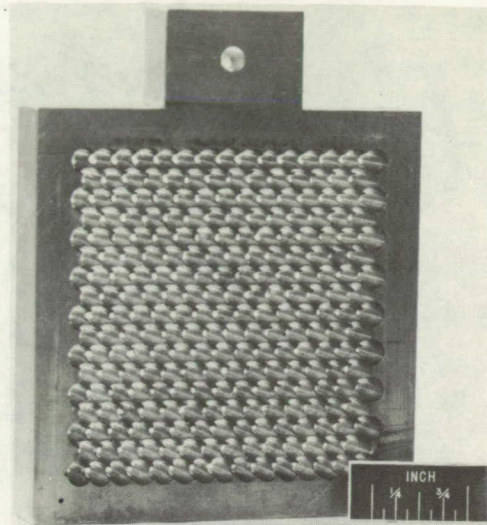
Corner detail, supersonic side

(a) Axially symmetric multinozzle; design Mach number, 3.46.

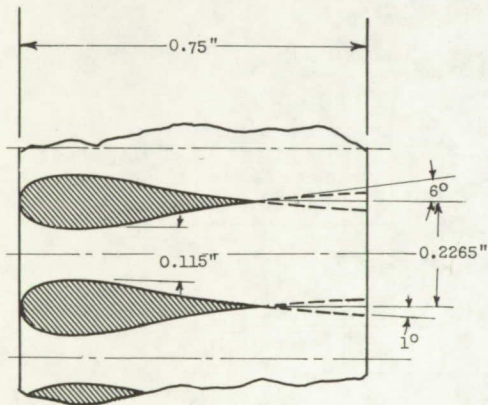
Figure 1. - Multinozzle details.



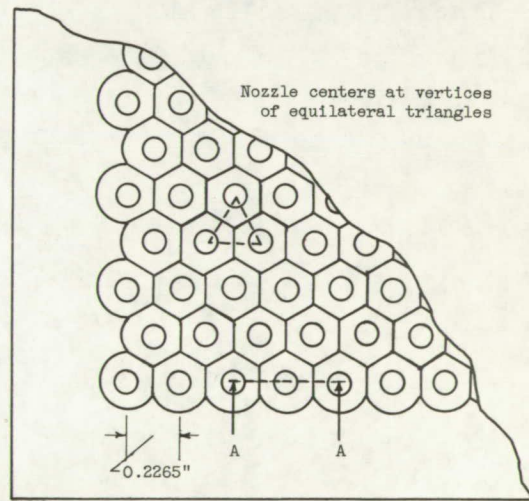
Subsonic side



Supersonic side



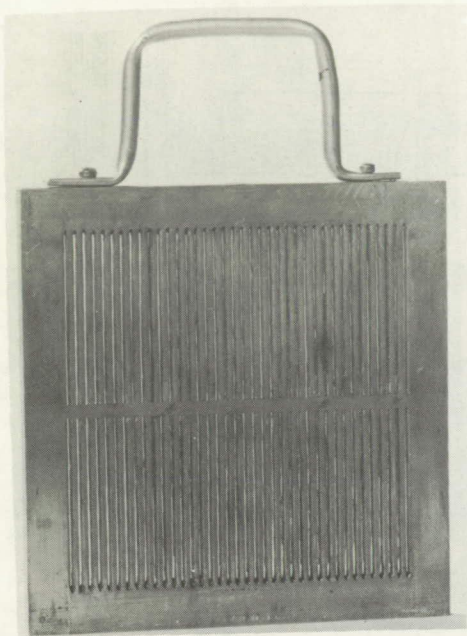
Section A-A
Single nozzle detail



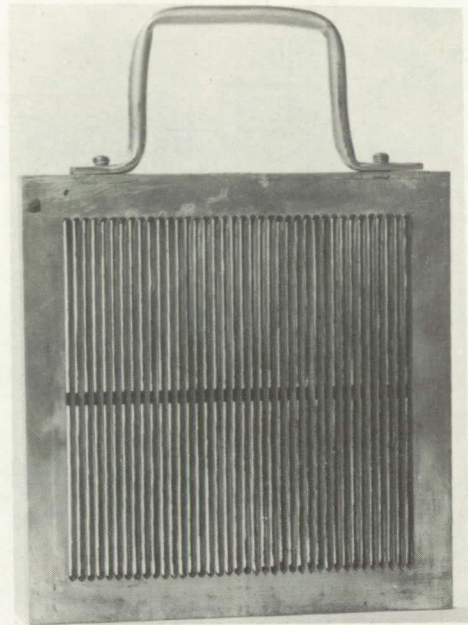
Corner detail, supersonic side

(b) Axially symmetric multinozzle; design Mach number, 3.07.

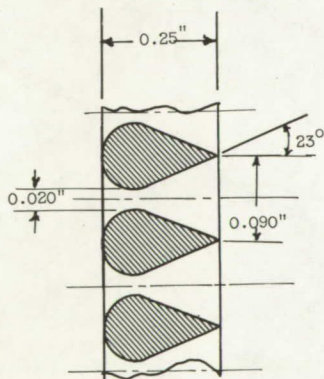
Figure 1. - Continued. Multinozzle details.



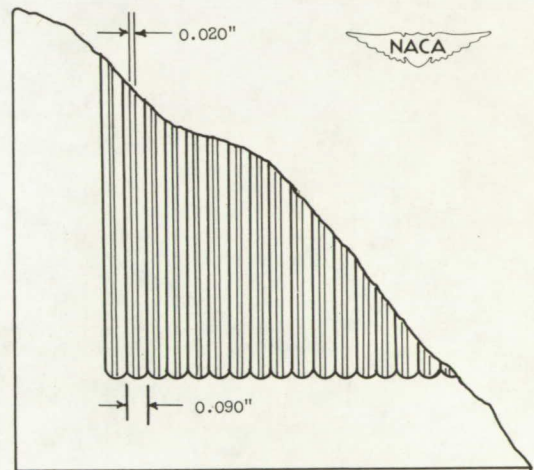
Subsonic side



Supersonic side



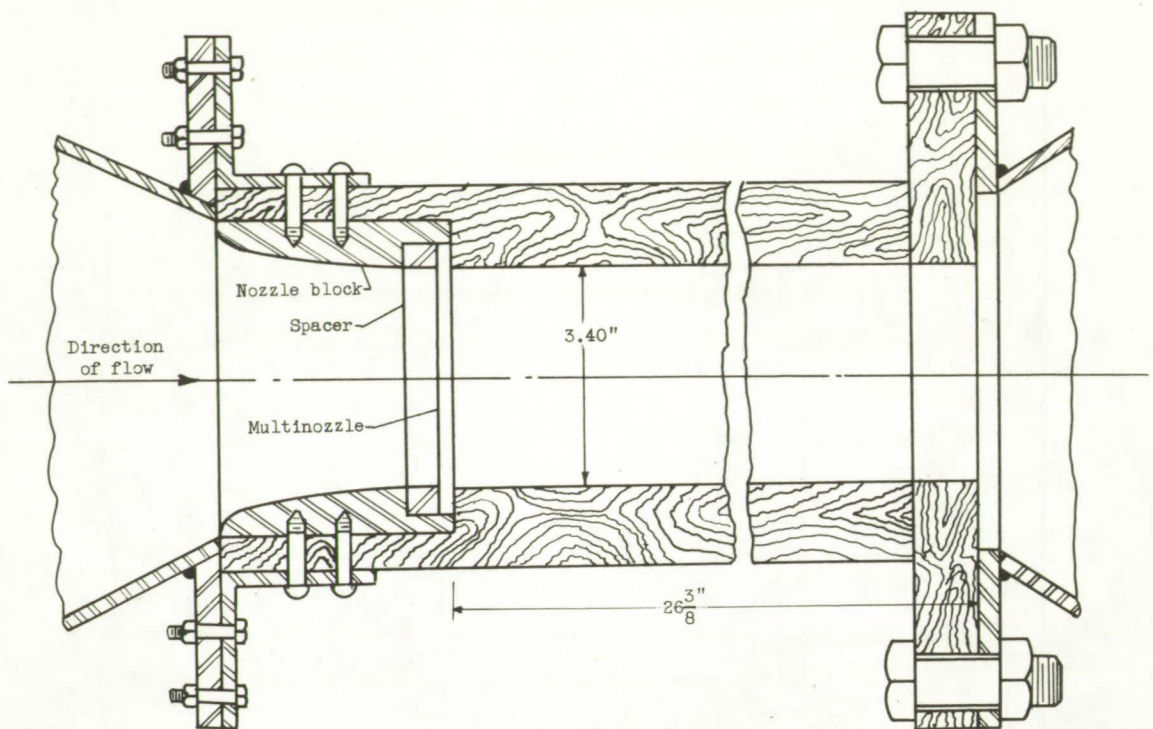
Single nozzle detail



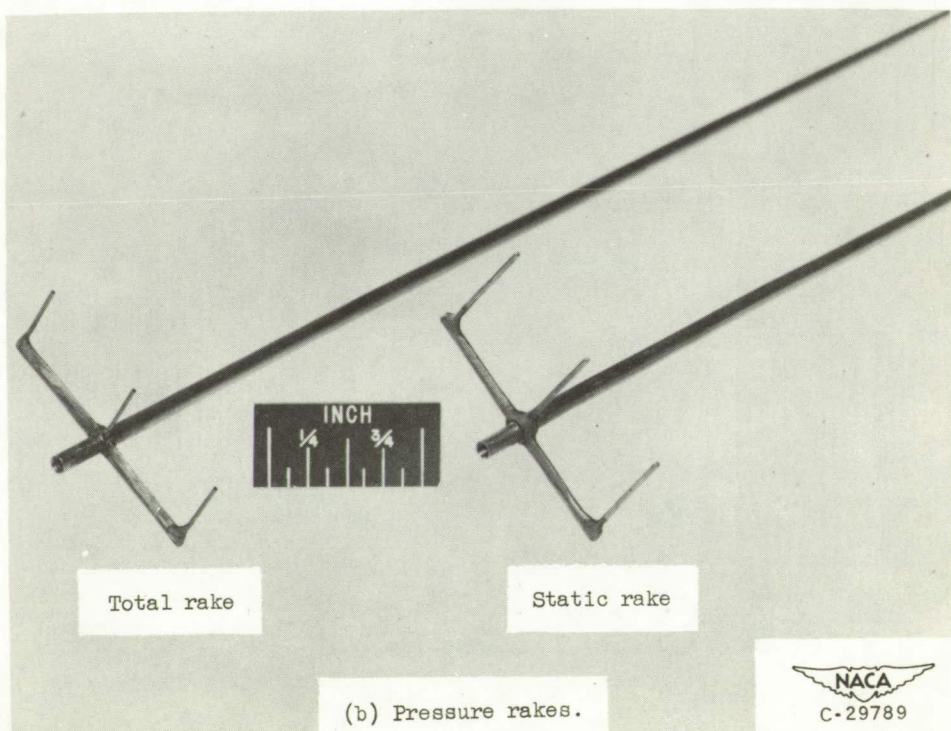
Corner detail, supersonic side

(d) Two-dimensional multinozzle; design Mach number, 3.07.

Figure 1. - Concluded. Multinozzle details.

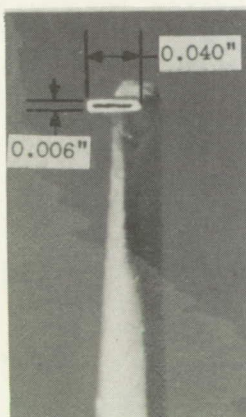
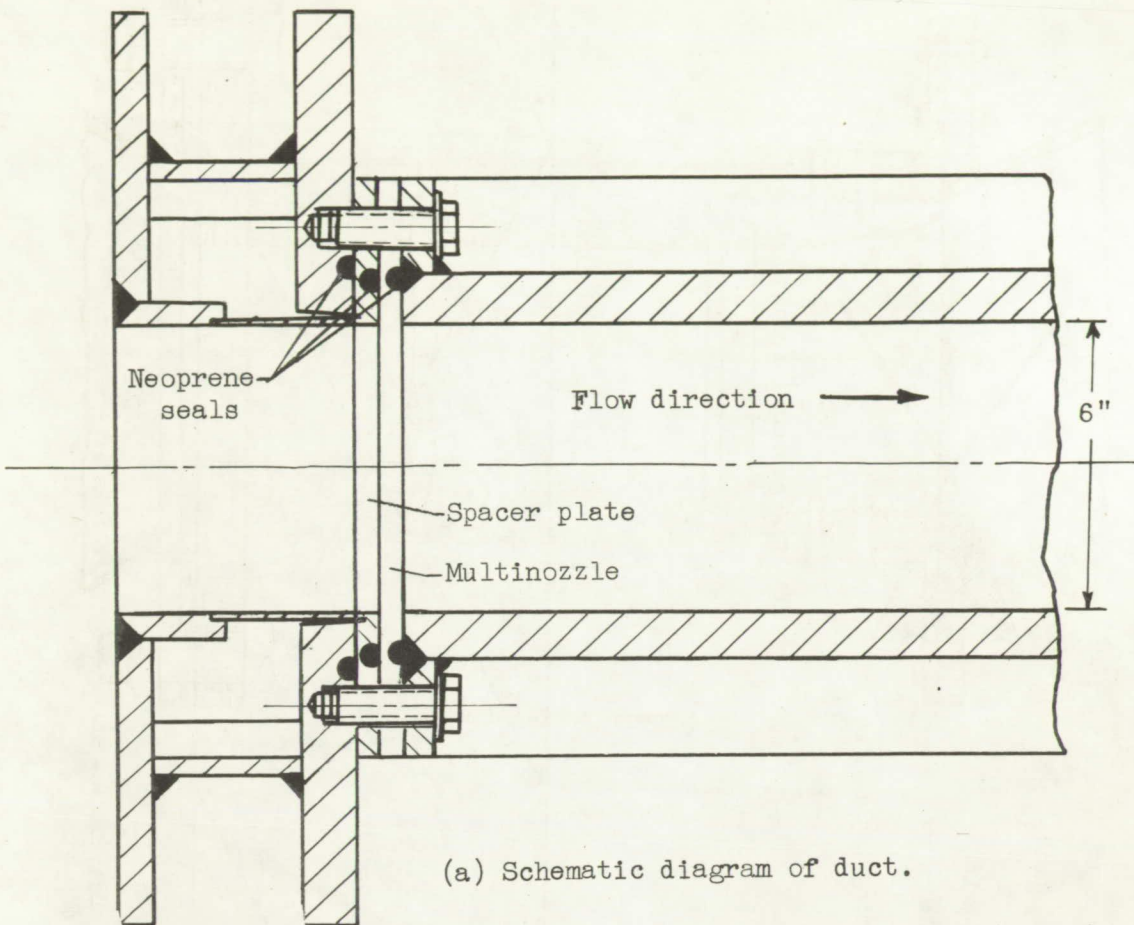


(a) Schematic diagram of duct.

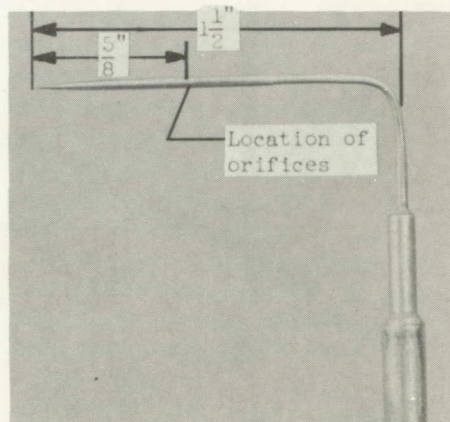
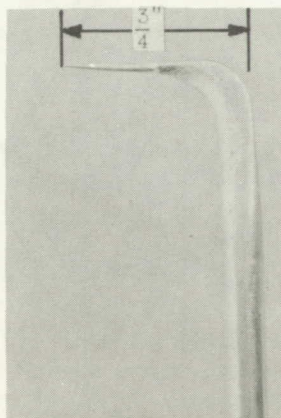


(b) Pressure rakes.

Figure 2. - 3.4- by 3.4-inch duct and instrumentation.



Pitot tube



Static probe

(b) Pitot-pressure and static-pressure survey probes used in 6"x6" channel.

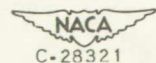


Figure 3. - 6- by 6-inch duct and instrumentation.

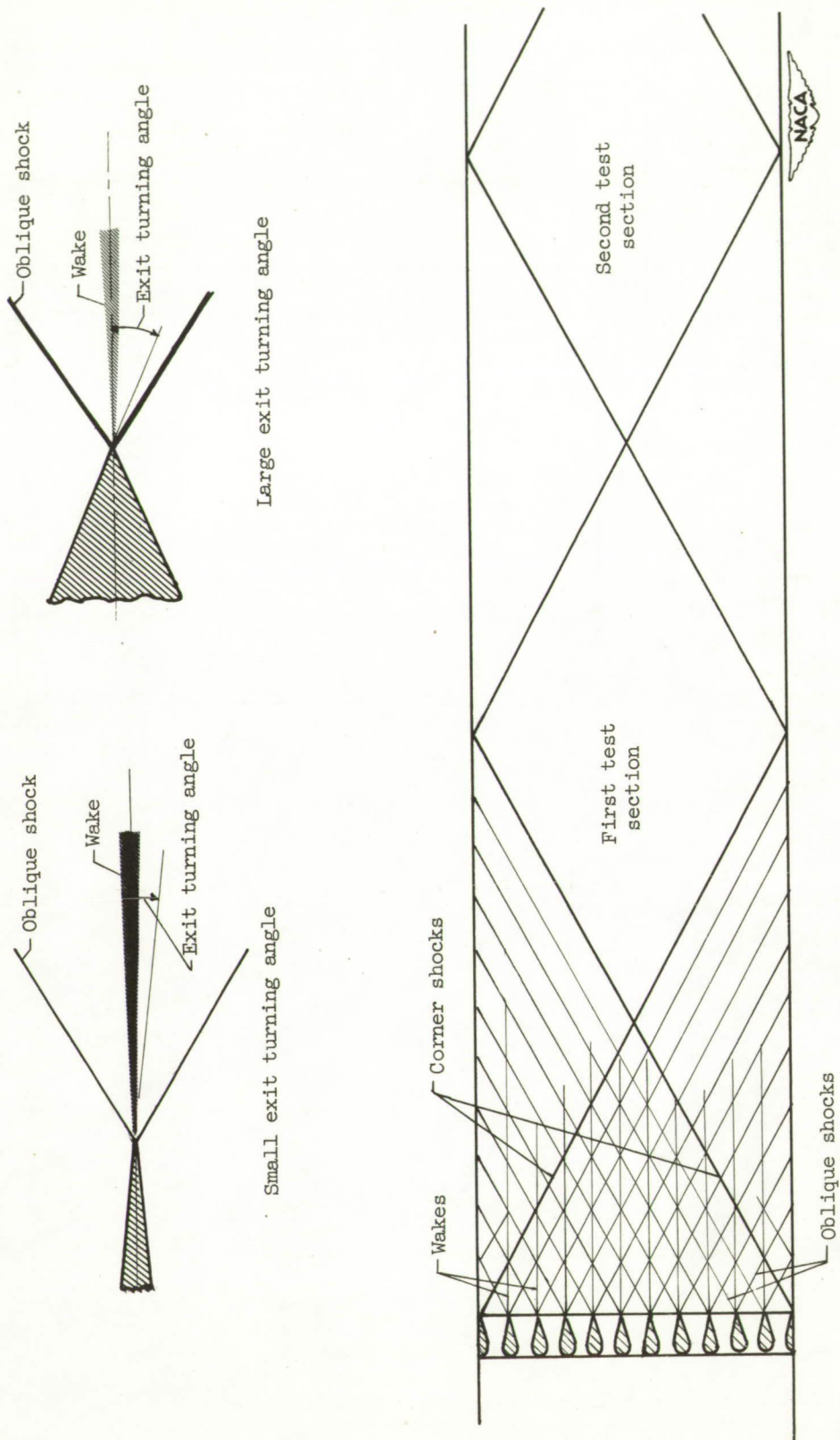
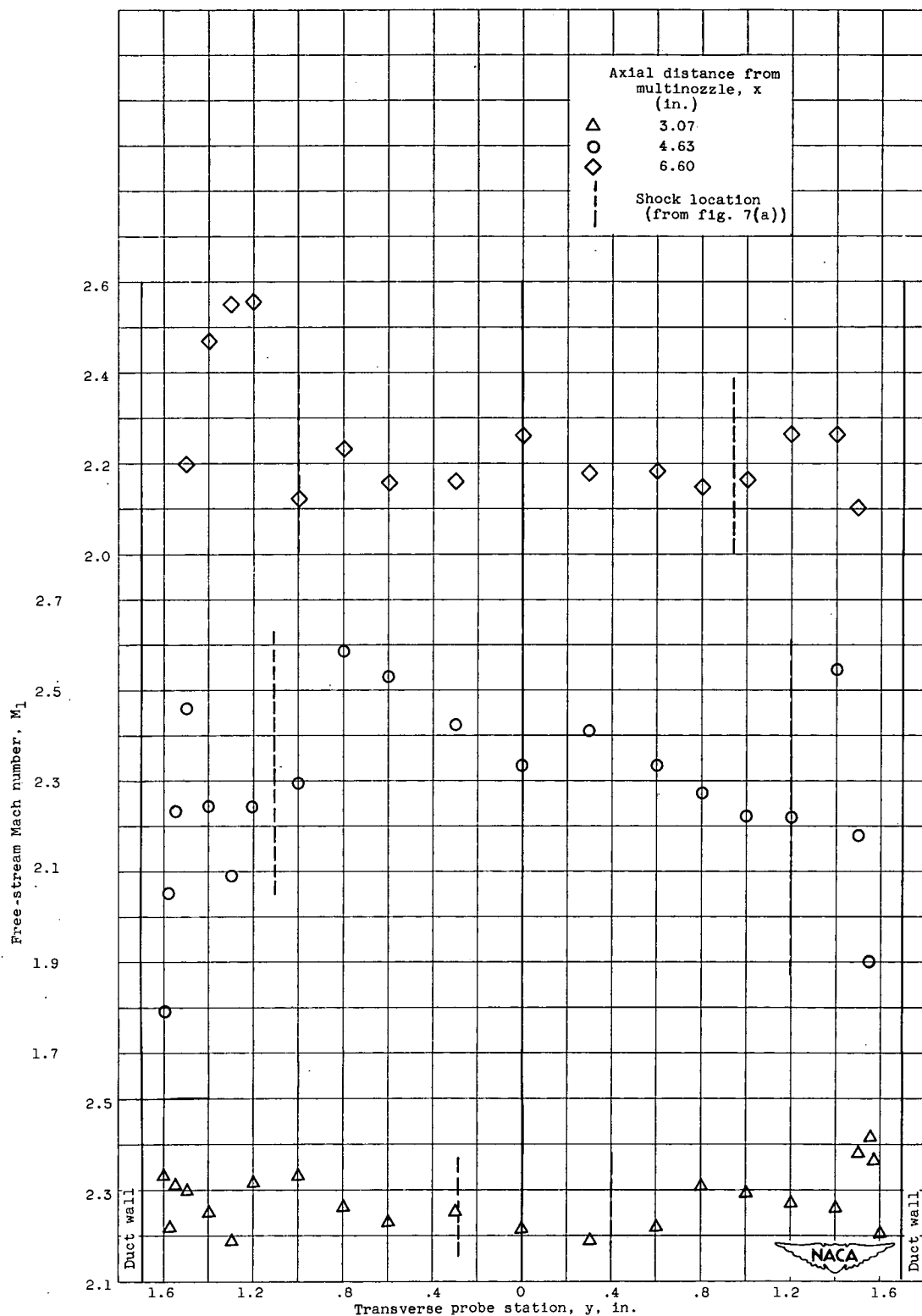
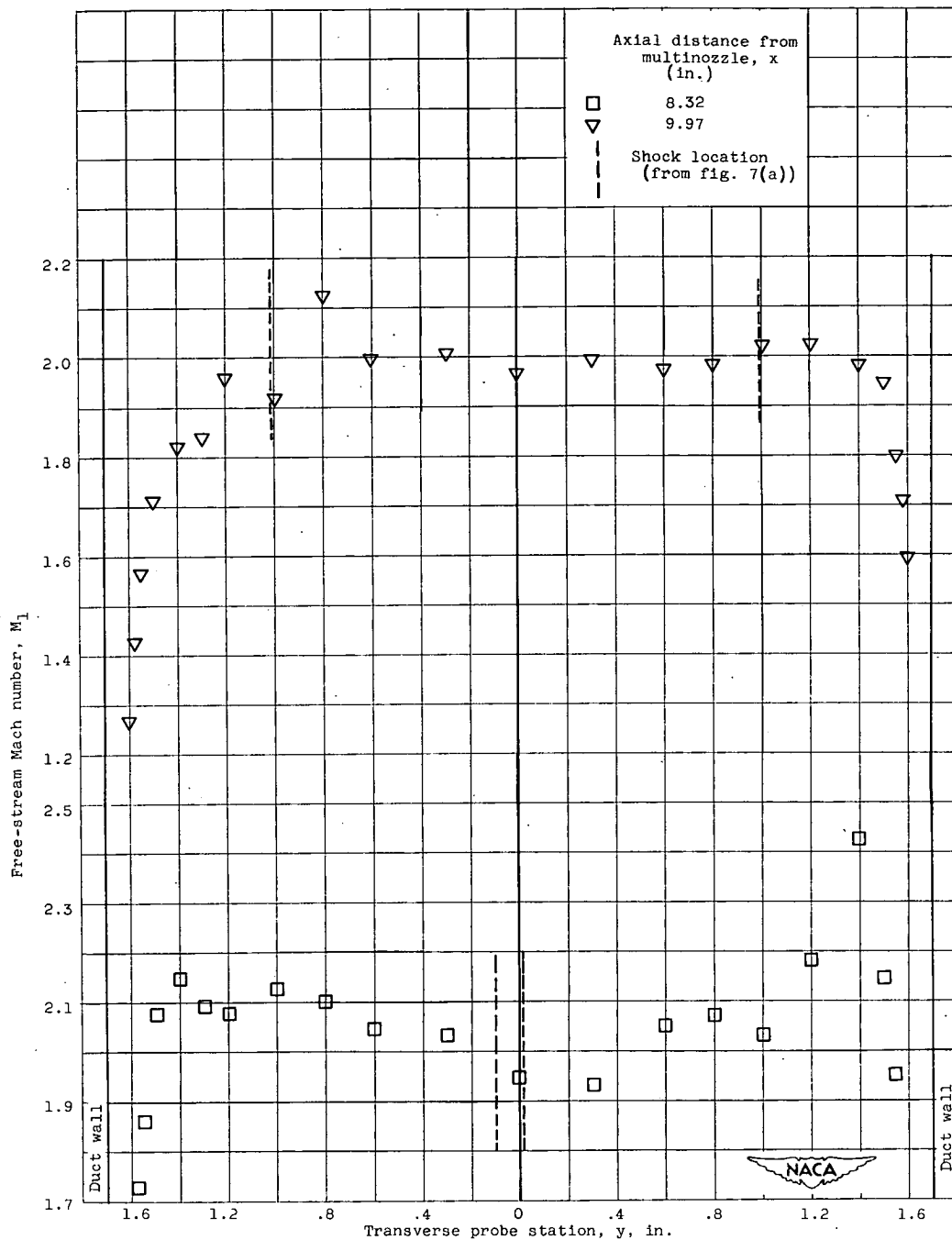


Figure 4. - Types of disturbance in flow downstream of multinozzle plates.



(a) Axially symmetric multinozzle; design Mach number, 3.46.

Figure 5. - Mach number distribution along transverse center line at several axial stations.



(a) Concluded. Axially symmetric multinozzle ; design Mach number, 3.46.

Figure 5. - Continued. Mach number distribution along transverse center line at several axial stations.

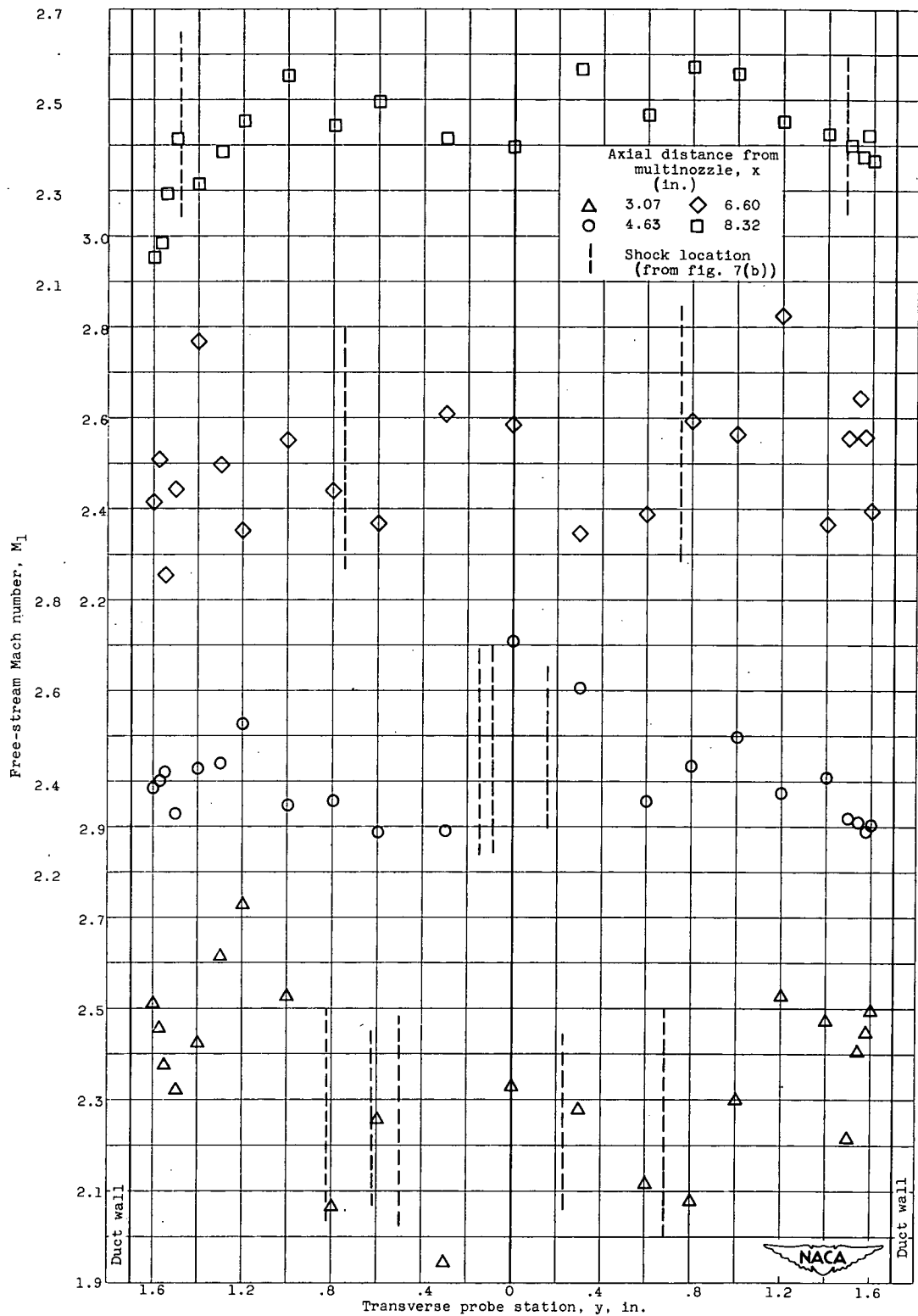
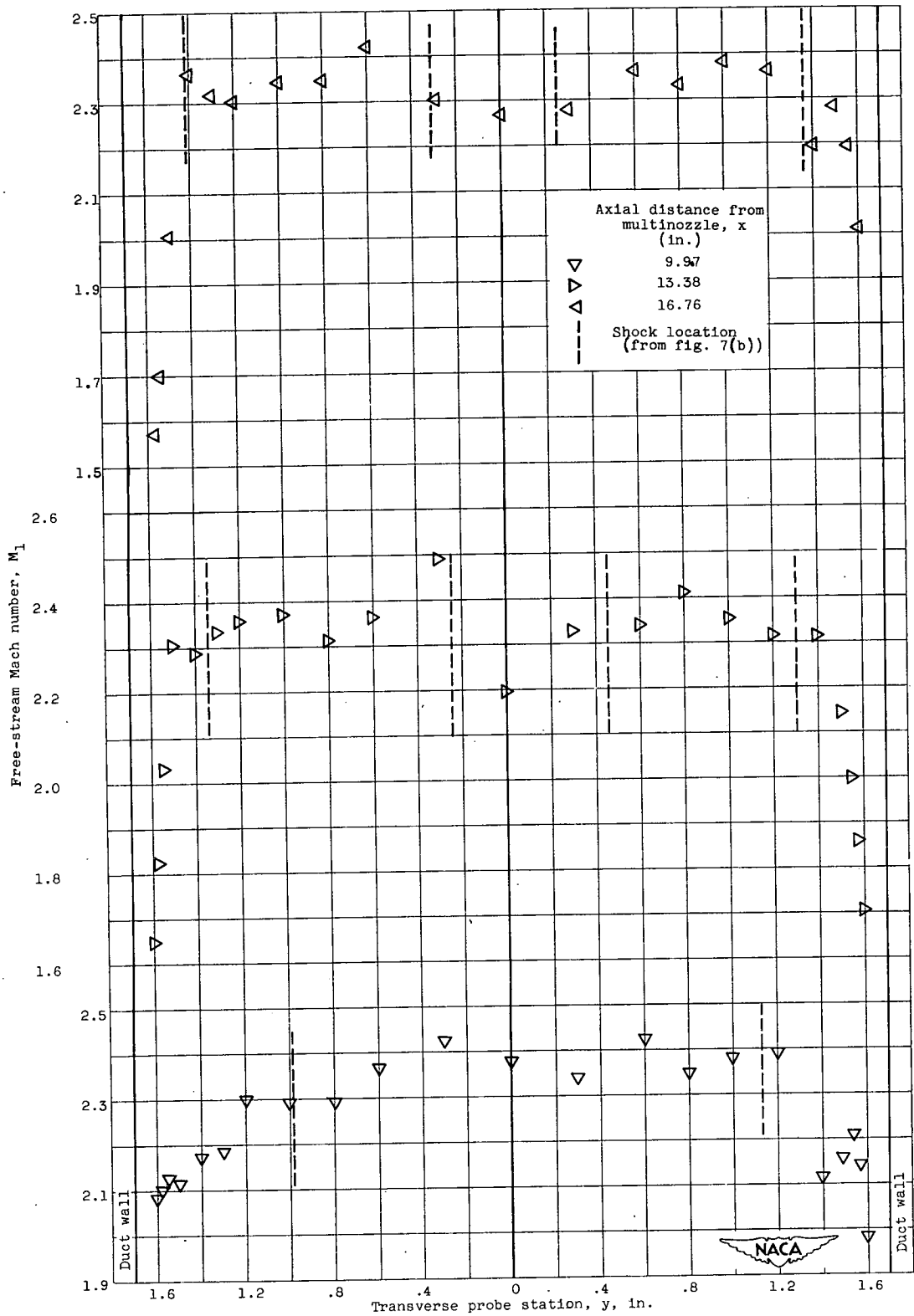
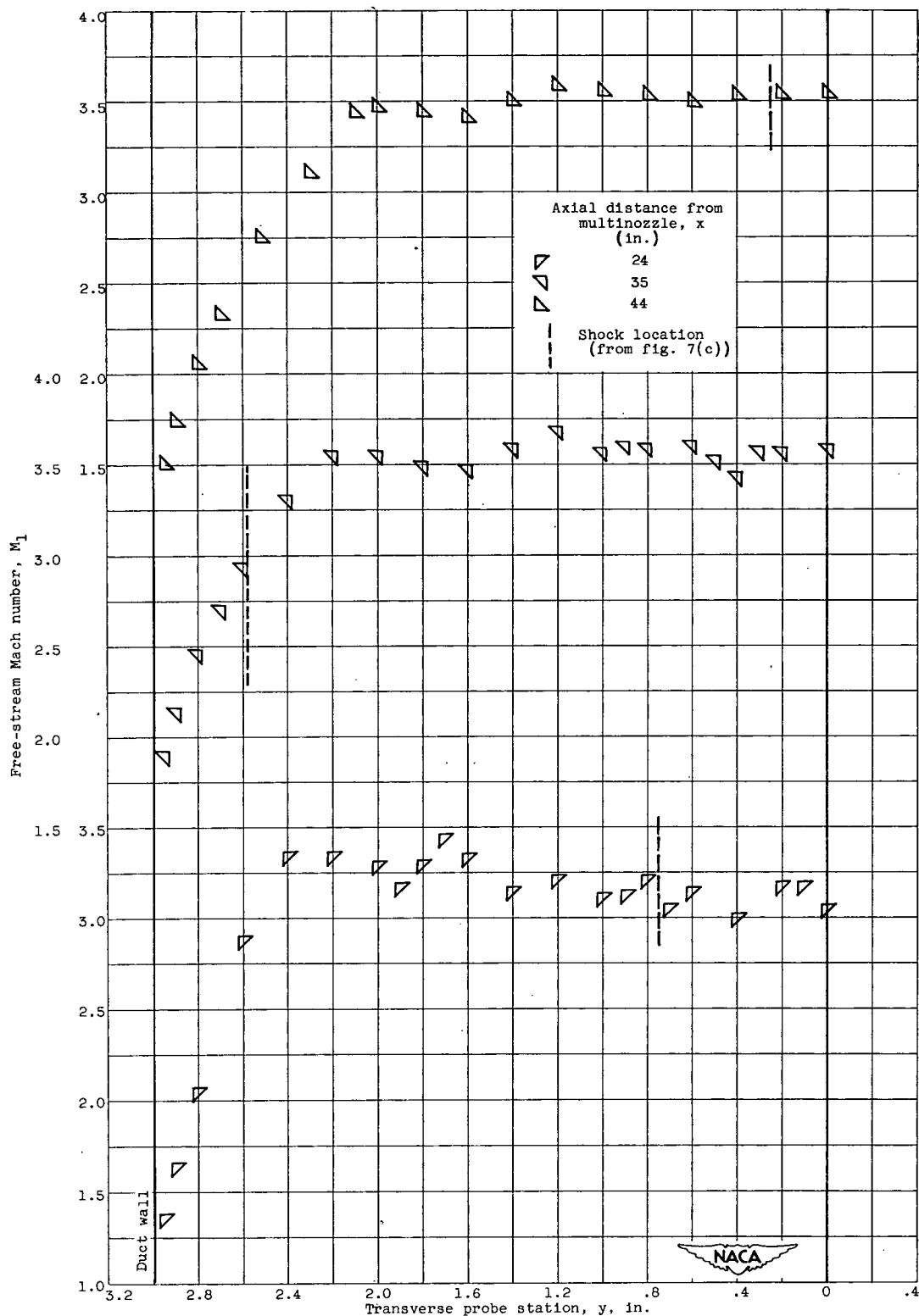


Figure 5. - Continued. Mach number distribution along transverse center line at several axial stations.



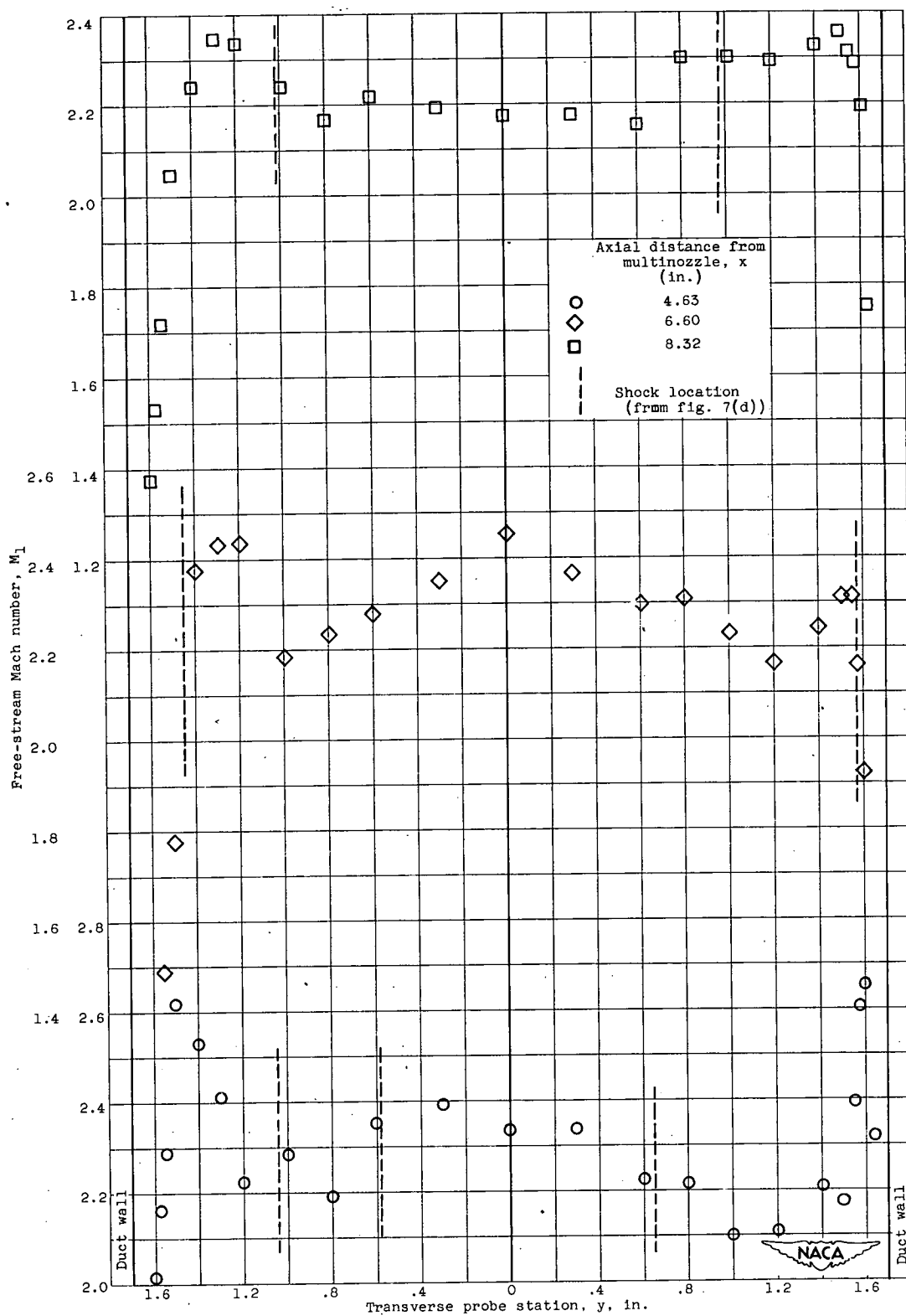
(b) Concluded. Axially symmetric multinozzle; design Mach number, 3.07.

Figure 5. - Continued. Mach number distribution along transverse center line at several axial stations.



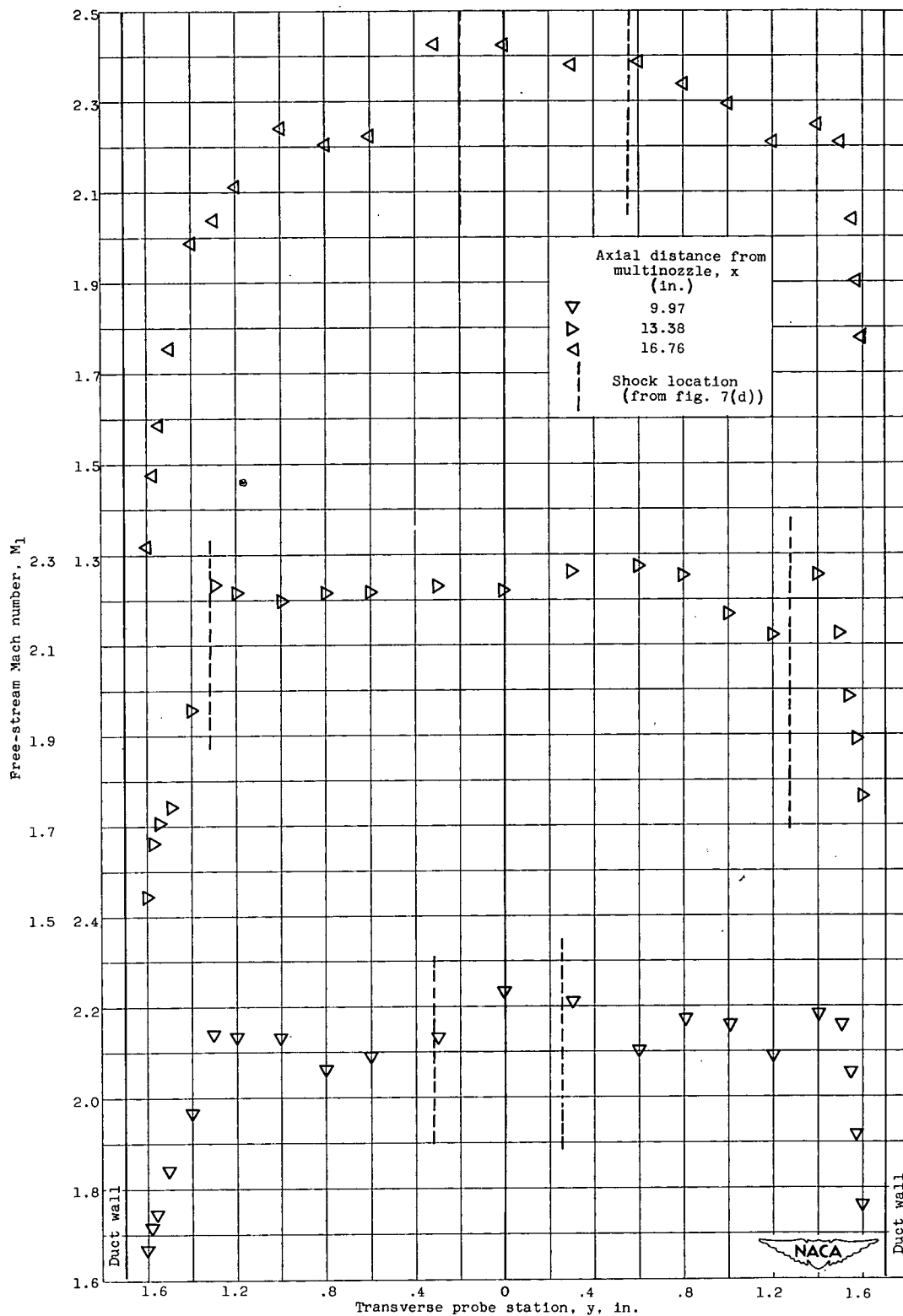
(c) Axially symmetric multinozzle; design Mach number, 7.01.

Figure 5. - Continued. Mach number distribution along transverse center line at several axial stations.



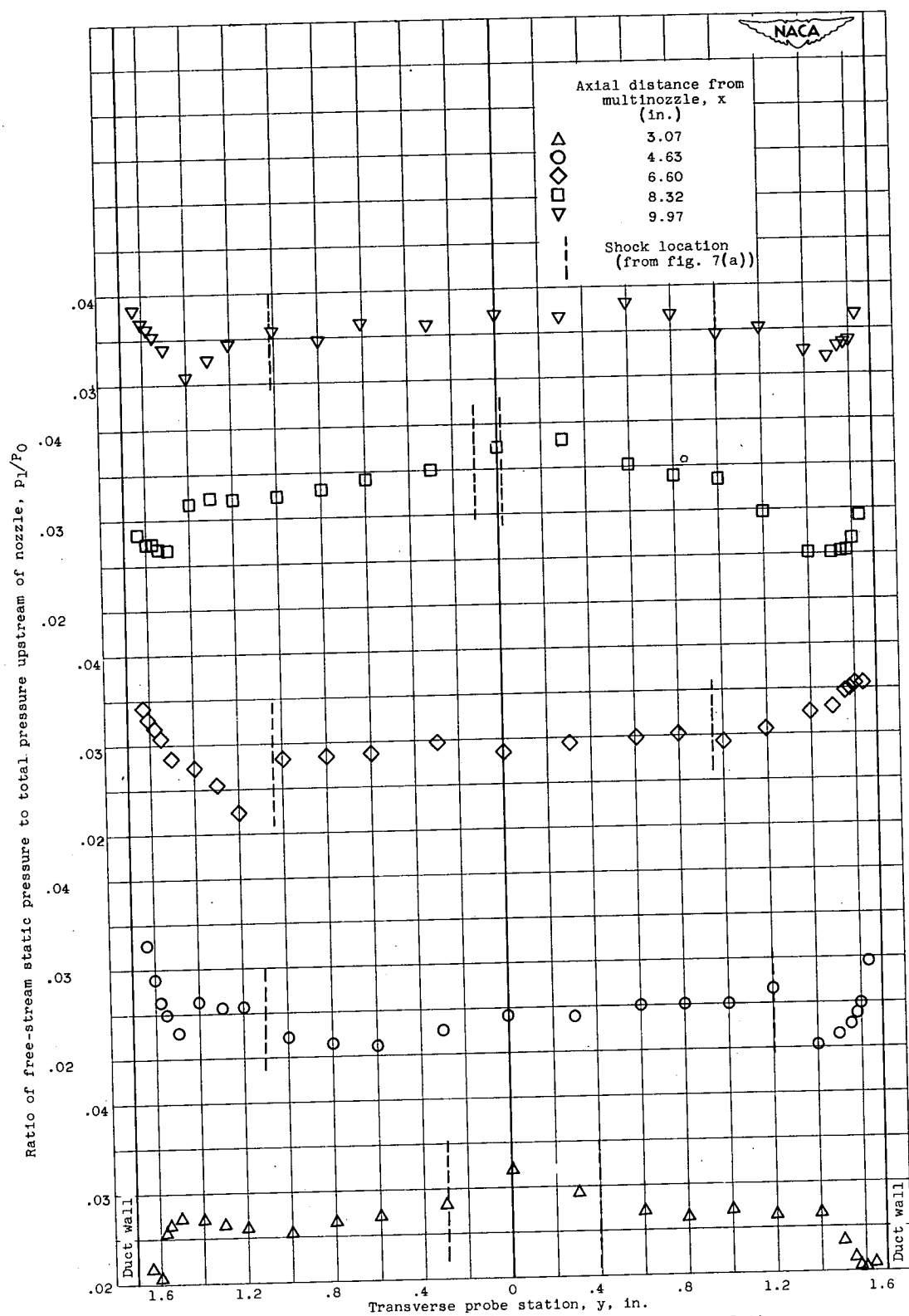
(d) Two-dimensional multinozzle; design Mach number, 3.07.

Figure 5. - Continued. Mach number distribution along transverse center line at several axial stations.



(d) Concluded. Two-dimensional multinozzle; design Mach number, 3.07.

Figure 5. - Concluded. Mach number distribution along transverse center line at several axial stations.



(a) Axially symmetric multinozzle; design Mach number, 3.46.

Figure 6. - Static-pressure distribution along transverse center line at several axial stations.

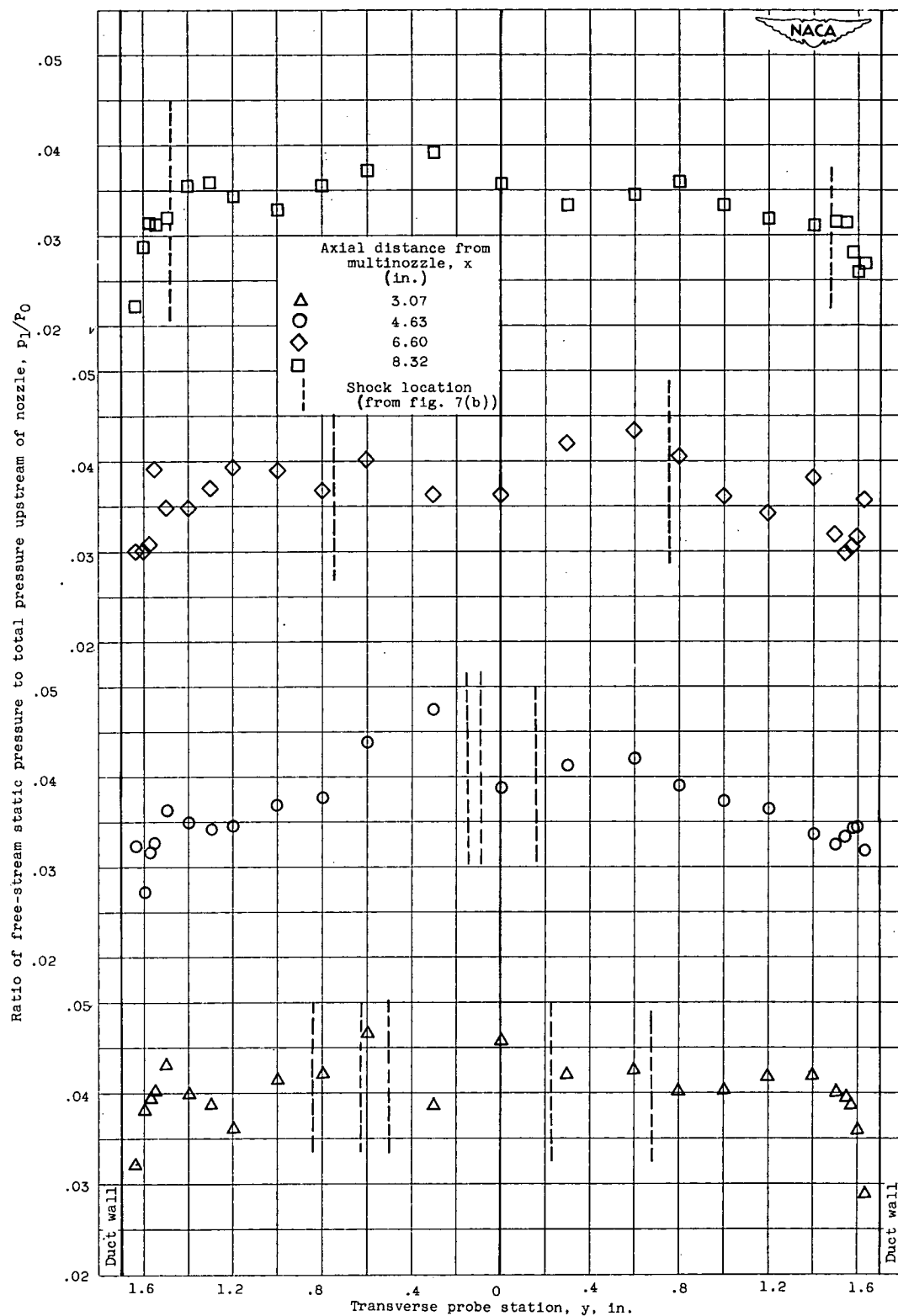
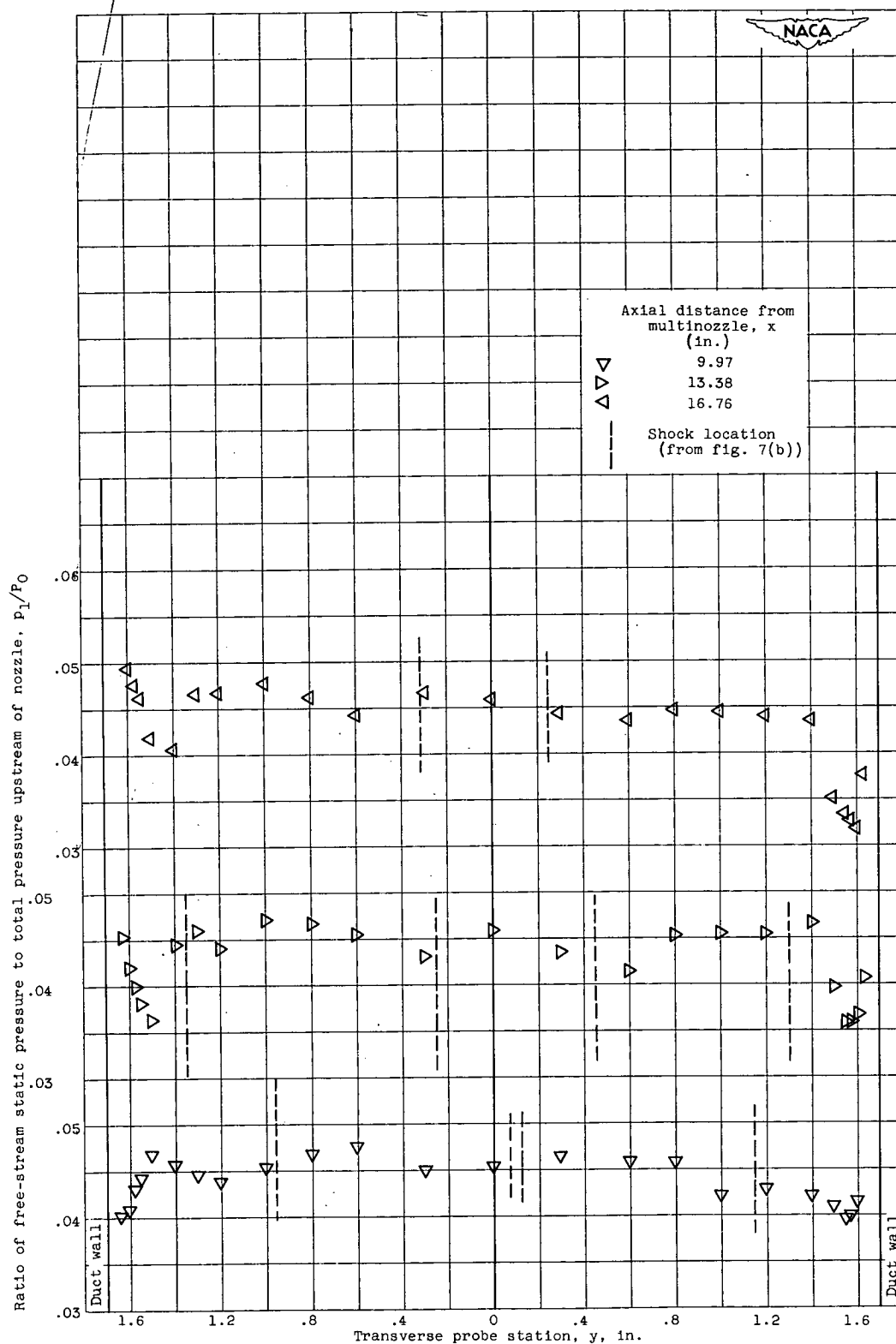
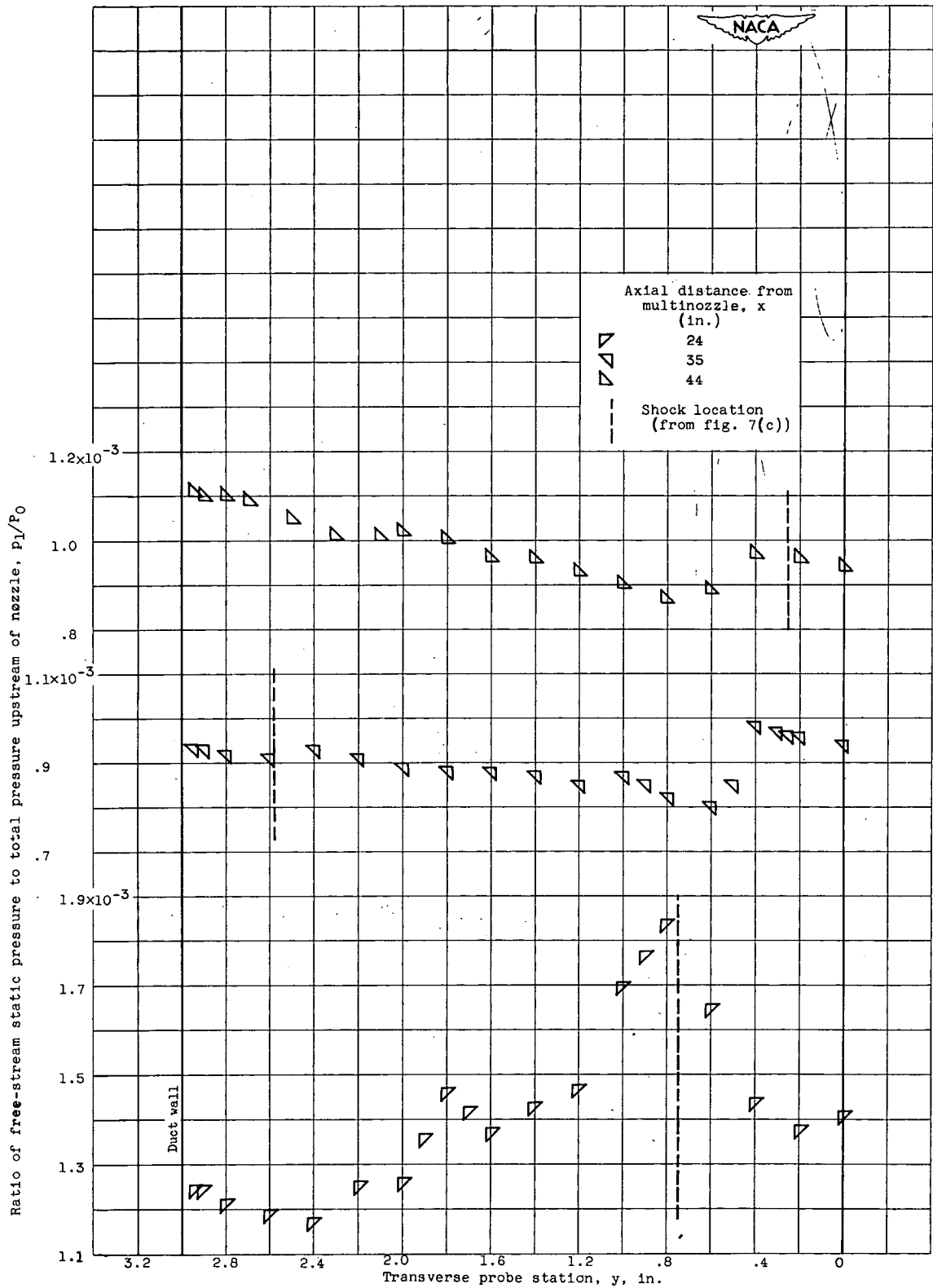


Figure 6. - Continued. Static-pressure distribution along transverse center line at several axial stations.



(b) Concluded. Axially symmetric multinozzle; design Mach number, 3.07.

Figure 6. - Continued. Static-pressure distribution along transverse center line at several axial stations.



(c) Axially symmetric multinozzle; design Mach-number, 7.01.

Figure 6. - Continued. Static-pressure distribution along transverse center line at several axial stations.

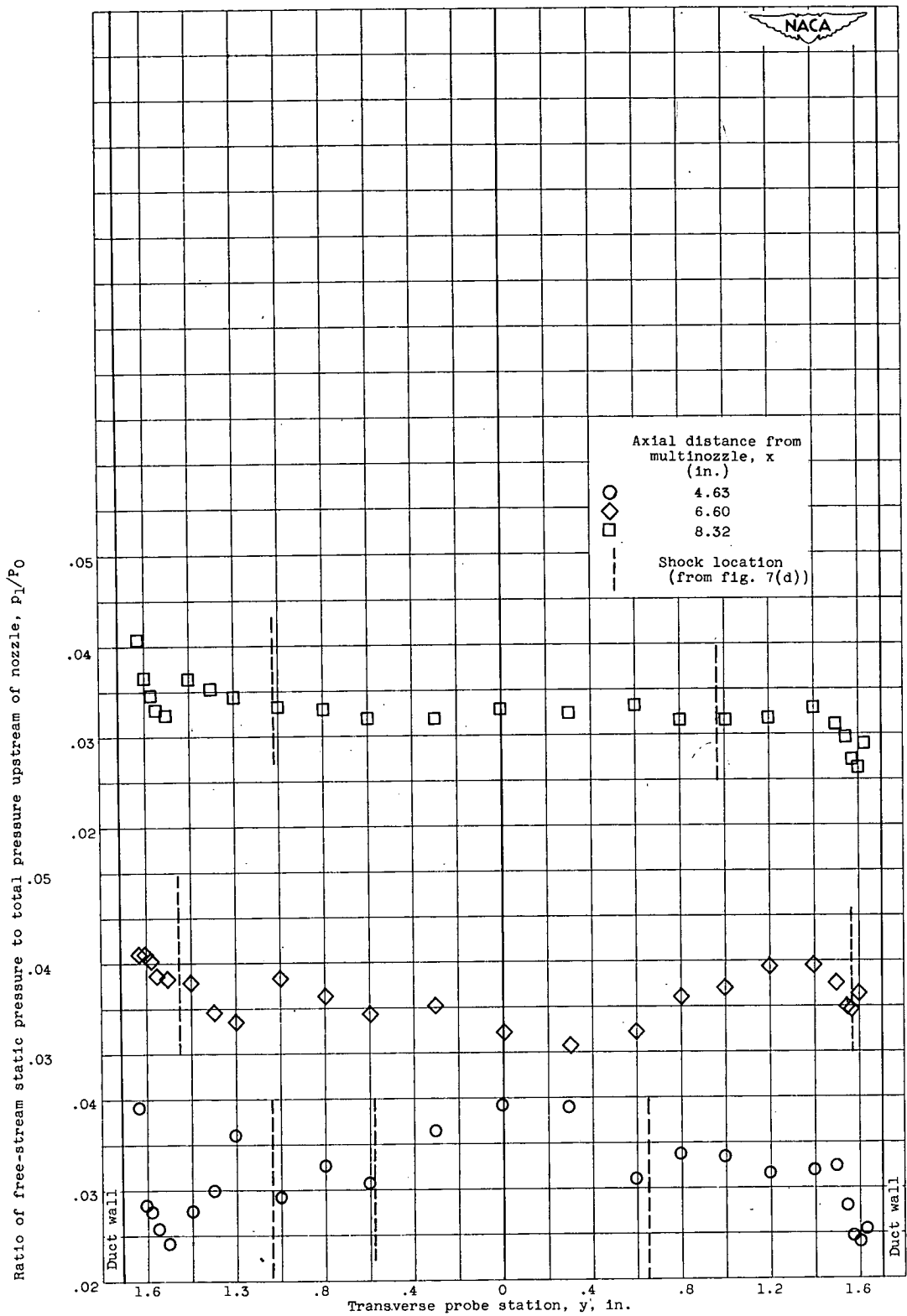
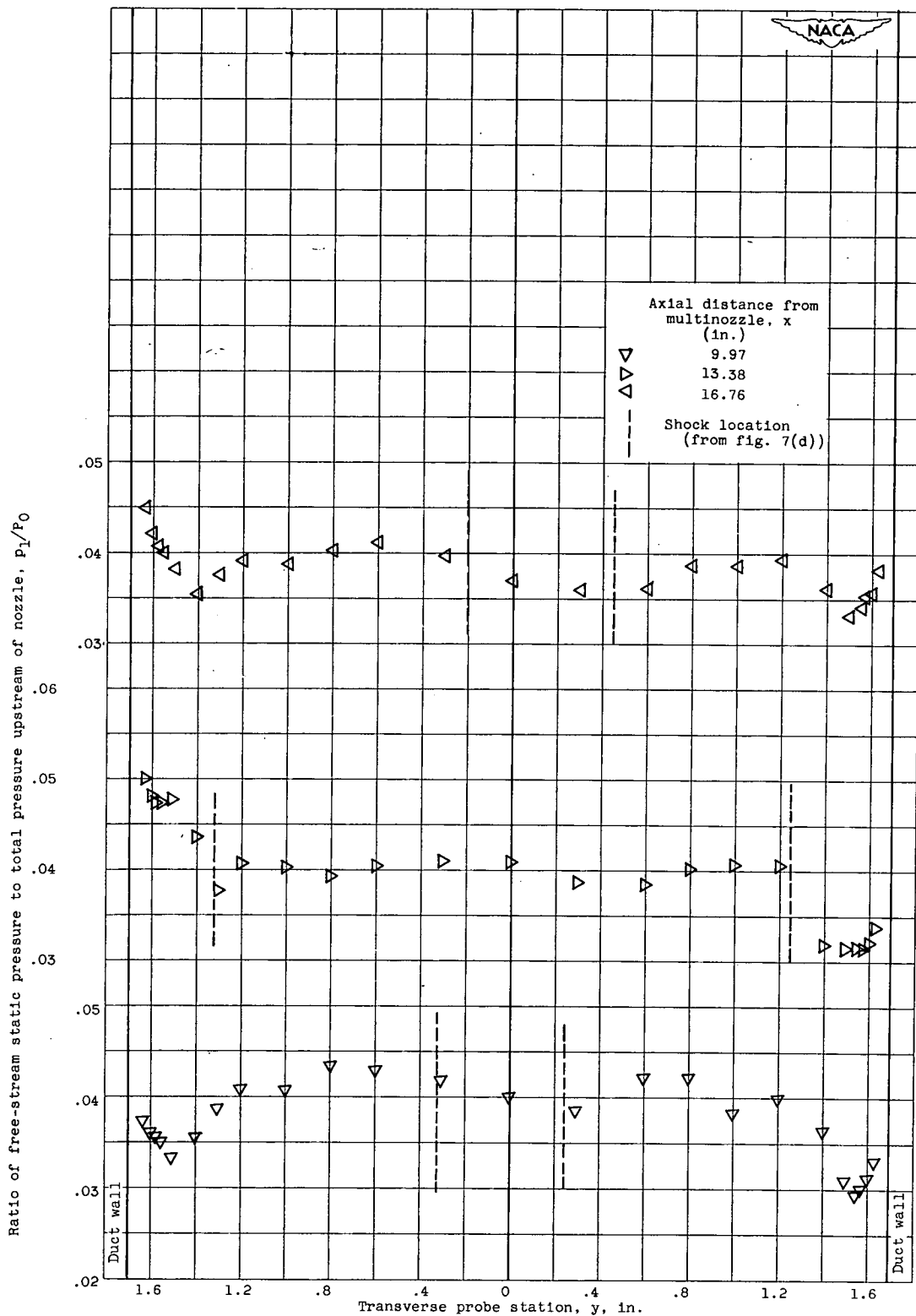
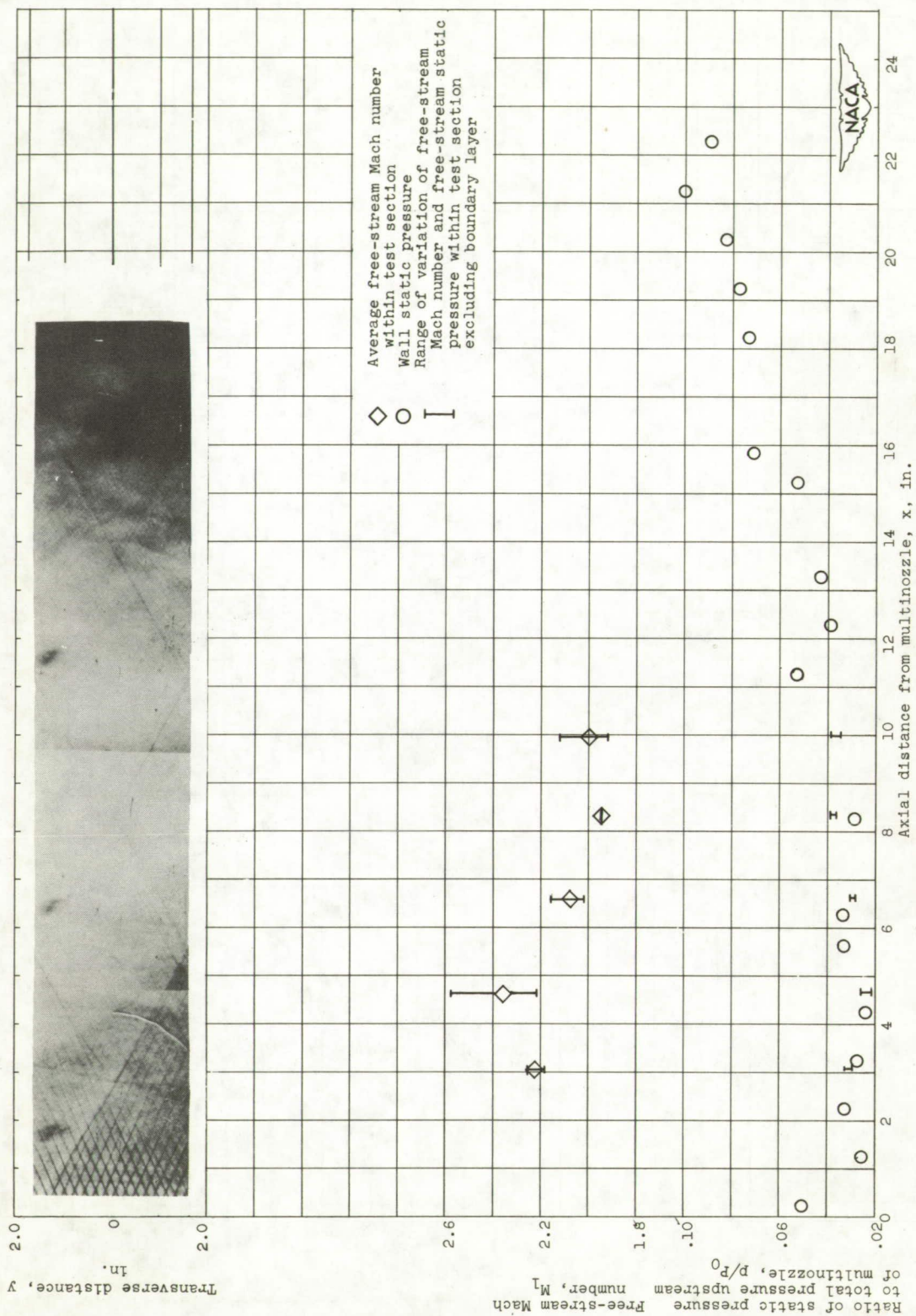


Figure 6. - Continued. Static-pressure distribution along transverse center line at several axial stations.



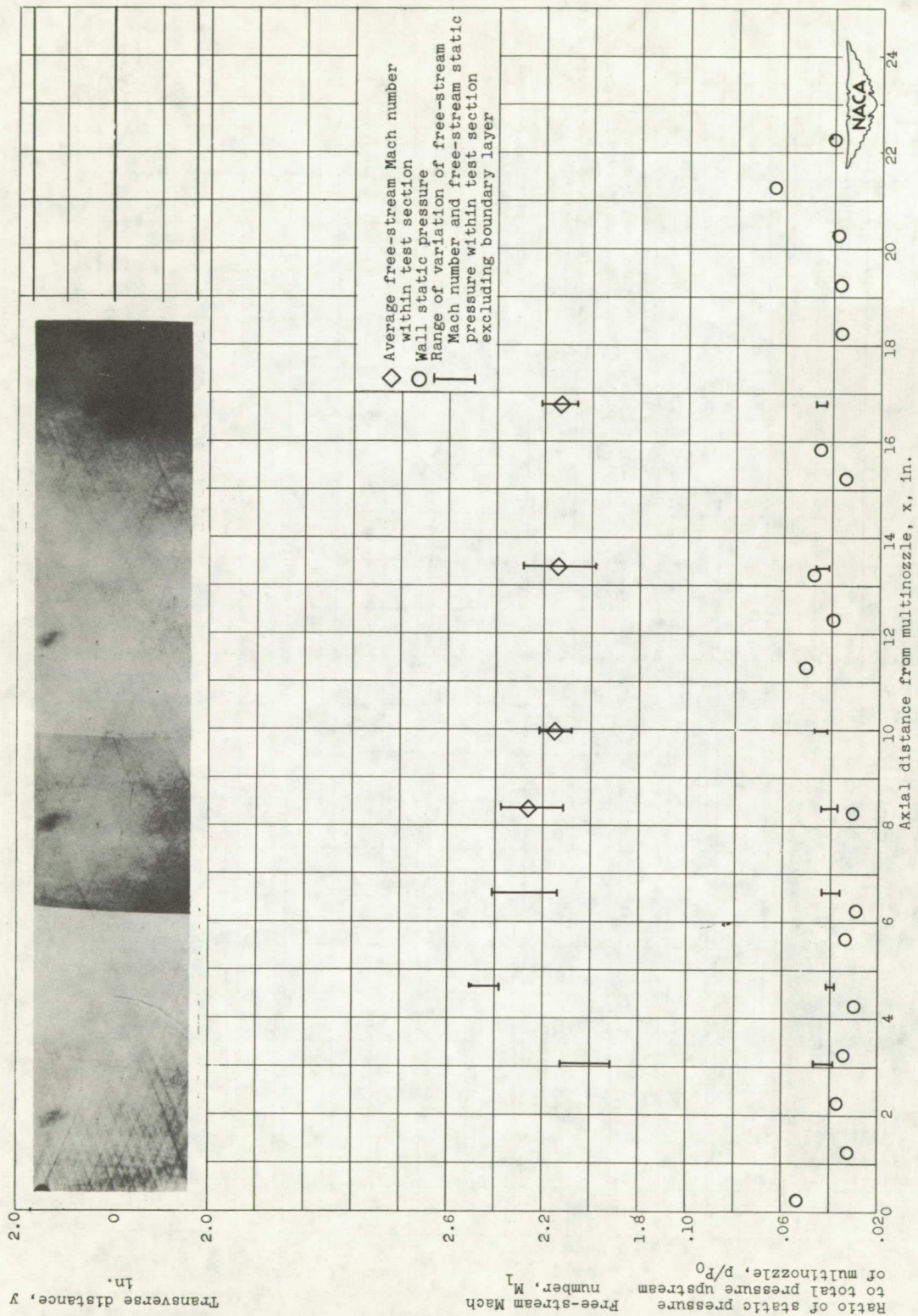
(d) Concluded. Two-dimensional multinozzle; design Mach number, 3.07.

Figure 6. - Concluded. Static-pressure distribution along transverse center line at several axial stations.



(a) Axially symmetric multinozzle; design Mach number, 3.46.

Figure 7. - Static-pressure and free-stream Mach number variation in axial direction and schlieren photograph.



(b) Axially symmetric multinozzle; design Mach number, 3.07.
Figure 7. - Continued. Static-pressure and free-stream Mach number variation in axial direction and schlieren photograph.

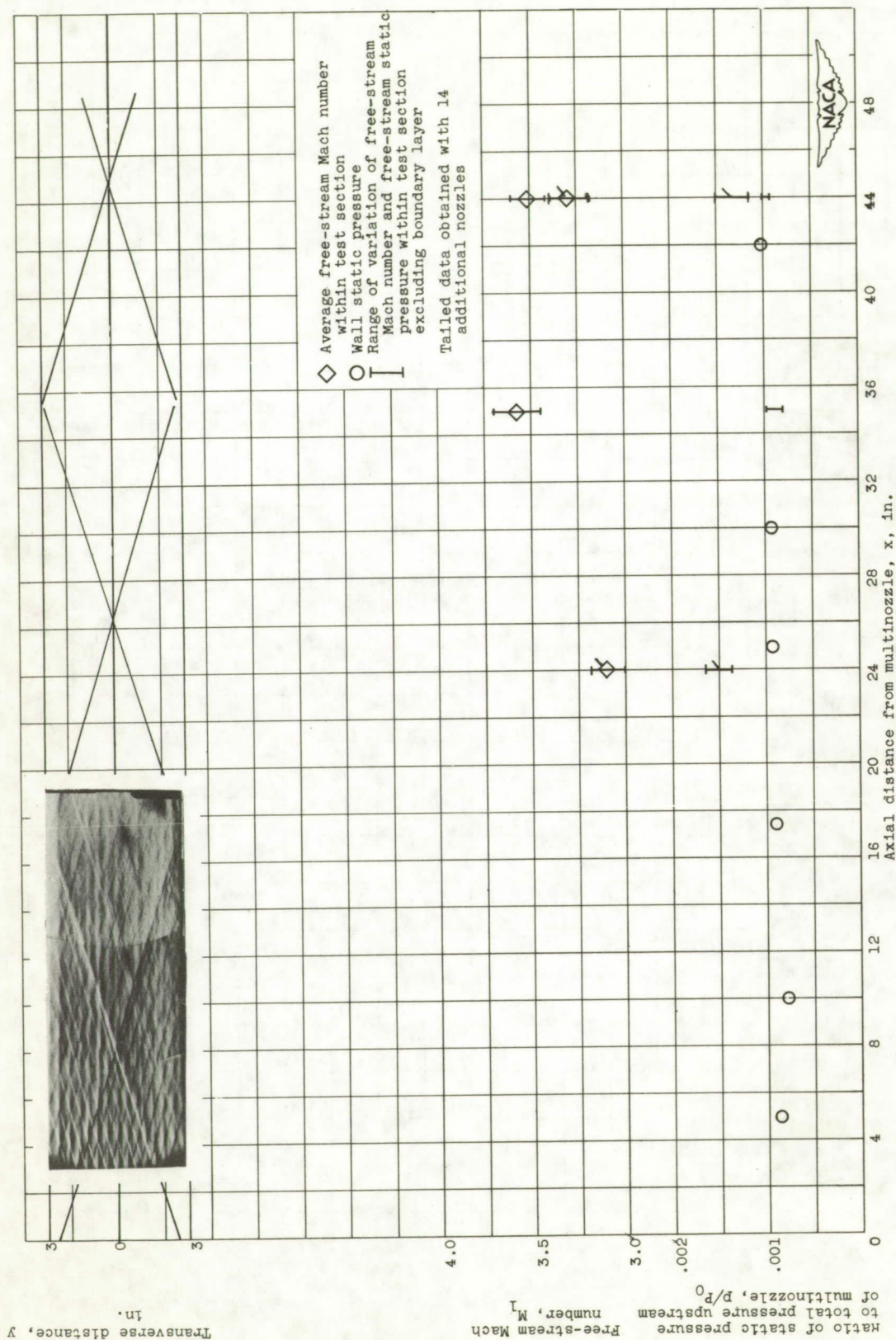
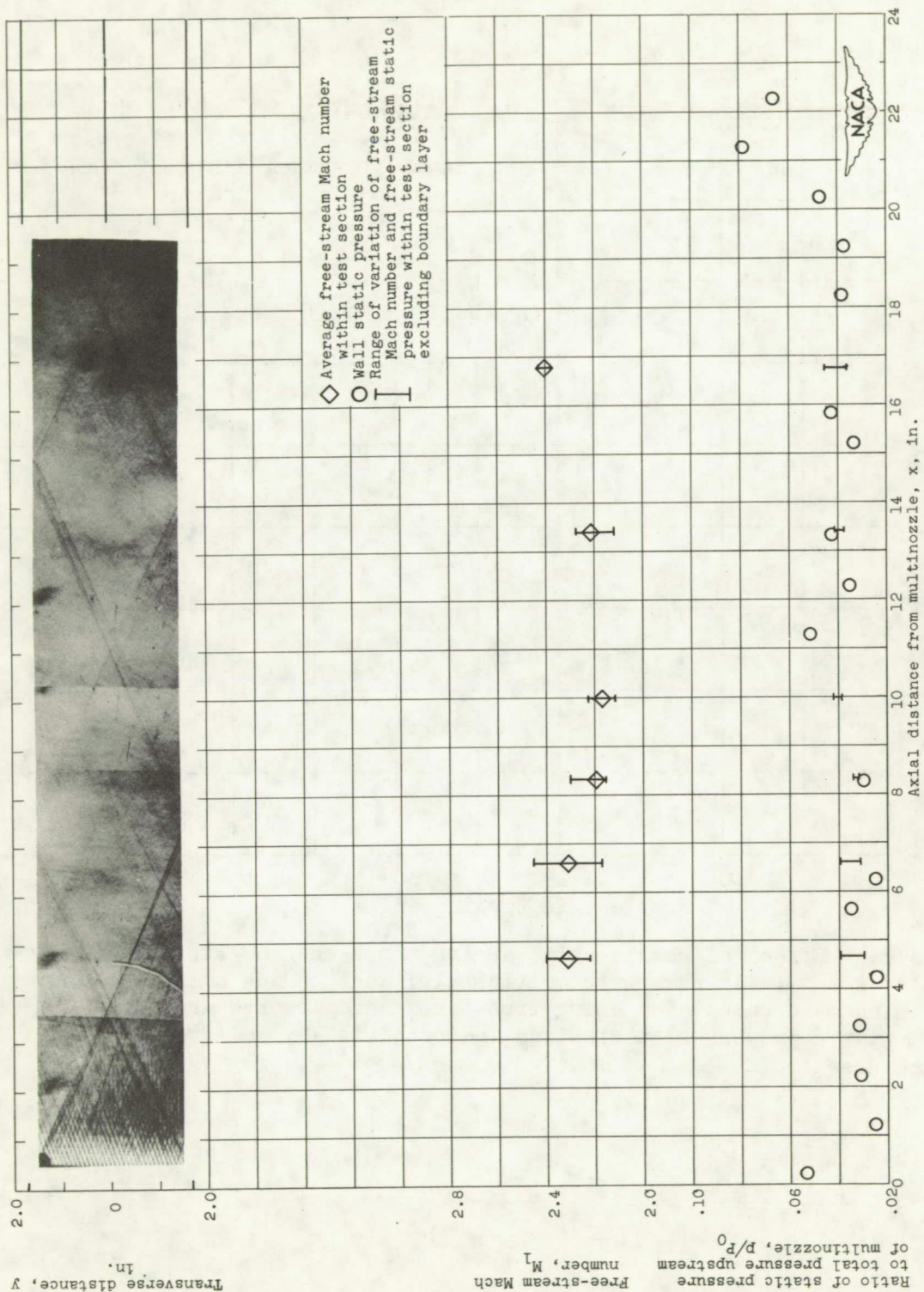


Figure 7. - Continued. Static-pressure and free-stream Mach number variation in axial direction and schlieren photograph.



(d) Two-dimensional multinozzle; design Mach number, 3.07.

Figure 7. - Concluded. Static-pressure and free-stream Mach number variation in axial direction and schlieren photograph.

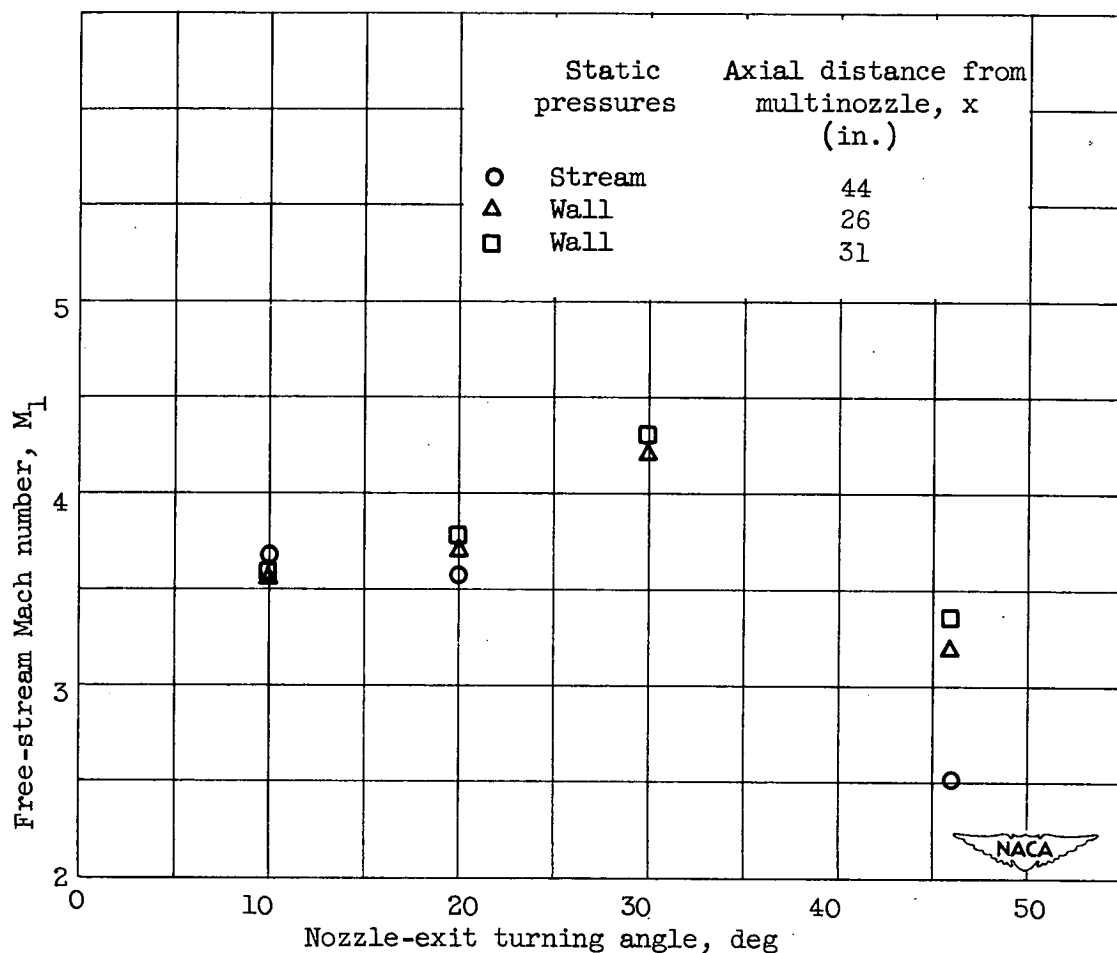


Figure 8. - Effect of nozzle-exit turning angle on free-stream Mach number for axially symmetric multinozzle; design Mach number, 7.01. (Mach numbers calculated using free-stream static pressures and wall static pressures at stations indicated in key and free-stream total pressure at $x = 44$ in.)

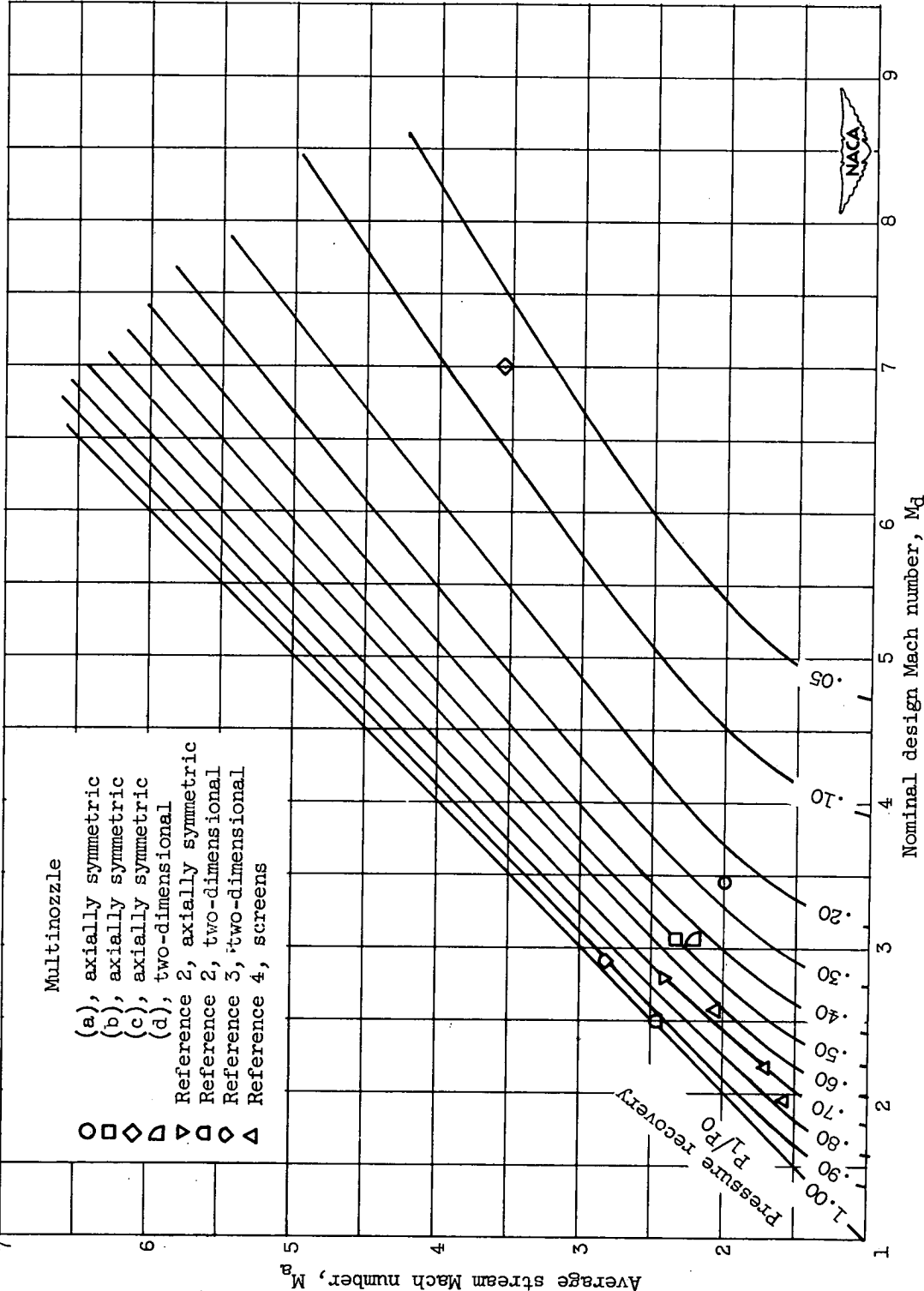


Figure 9. - Multinozzle comparison.